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THE AIR FORCE WEAPONS LABORATORY SKID RESISTANCE RESEARCH PROGRAM, 1969-1974

George D. Ballentine

Air Force Weapons Laboratory
Kirtland Air Force Base, New Mexico

May 1975

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Final Report for Period 1 July 1969 - 30 June 1974

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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A summary is presented of research done on airfield pavement skid resistance at the Air Force Weapons Laboratory during the years 1969-1974. Included are a description of the standard skid resistance evaluation procedures developed by the Weapons Laboratory, a summary of research work done in the area of antihydroplaning surface treatments, and a summary of information gained from study of skid-resistance data from some 14 airfields.

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This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico 87117, under Project 683M, Task 4, and Program Element 63723F. Major George D. Ballentine (AFCEC/OL-AA) was the Laboratory Project Officer-in-Charge.

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FOREWORD

The author wishes to recognize the efforts of the many persons who contributed to the accomplishments of the Air Force Weapons Laboratory skid-resistance research program over a 5-year period. Chief among these persons are Major Guy P. York, Major Phil V. Compton, and Lt Calvin Hickey who were formerly assigned to the Weapons Laboratory and worked on various facets of the program. The work of personnel at the Civil Engineering Research Facility, University of New Mexico, contributed greatly to the success of the program. Among those persons, the efforts of Mr. Emil Hargett, Mr. Steve Scales, and Mr. Billy Brewer are most significant.

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SECTION I

INTRODUCTION

The Air Force, as well as the civilian aviation community, has become increasingly concerned with aircraft landing safety during inclement weather. This concern has been prompted by the increased landing speeds of jet aircraft, together with the increased number of wet-weather landings permitted by improved flight instruments and instrumented landing systems. Adequate pavement traction has become a major safety concern to prevent loss of directional control and stopping capability of the aircraft during landings on wet pavement. During the last six years (1968 - 1973) the number of accidents attributed directly to aircraft wheel hydroplaning has increased. This trend for accidents involving USAF aircraft is shown graphically in figure 1.

Since the early 1960s when the problem was first apparent, an effort has been underway to develop a technique to assess runway conditions and to let the pilot know what to expect when he lands. One of the early devices developed and used for this purpose was the James Brake Decelerometer (or Inspection Decelerometer). This device consisted basically of a pendulum and an indicating needle; the needle recorded the deceleration due to displacement of the pendulum to which it was attached. The device was made in such a way that the needle registered maximum displacement and had to be manually reset after each reading. The James Brake Decelerometer, mounted in a stock vehicle (sedan or station wagon) became standard Air Force equipment to determine the Runway Condition Reading (RCR) of the pavement, a number that could vary from 01 to 26. These numbers provided the pilot a means of estimating how his aircraft would interact with the pavement surface when he landed.

Unfortunately, results from the James Brake Decelerometer were often not repeatable, i.e., results were affected by a number of variables - the driver of the vehicle, the vehicle itself, and the techniques used in making the test. It soon became apparent that this device was not the answer to the question of how to measure skid-resistance properties of runways; therefore, a better method was sought.

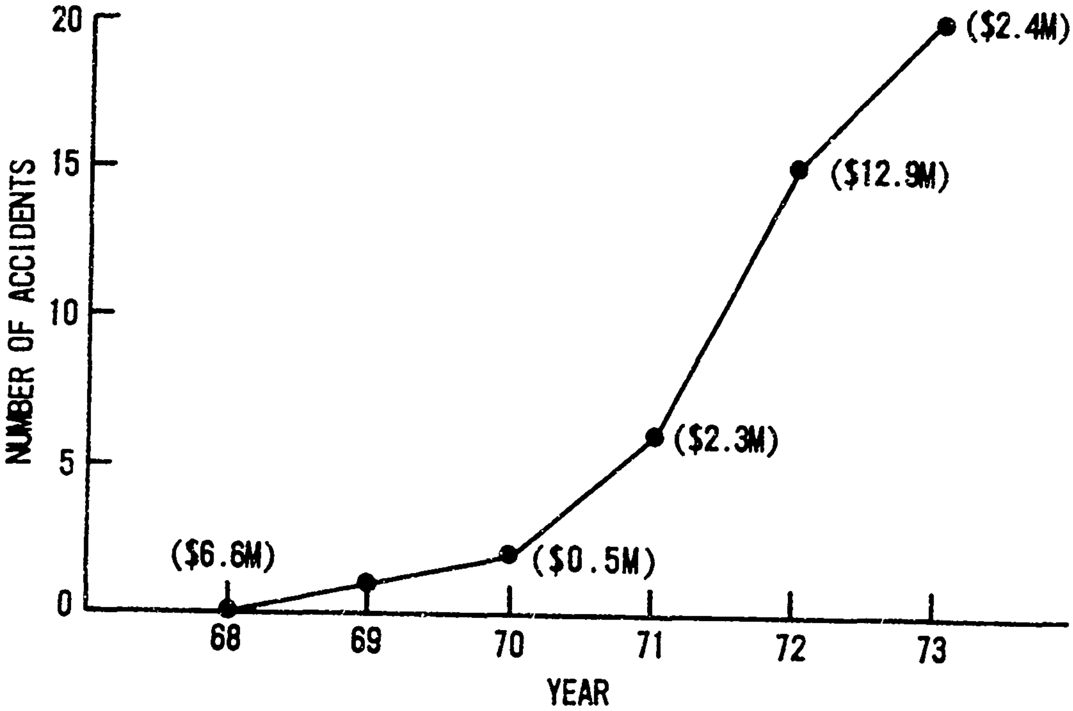


Figure 1. USAF Aircraft Accidents Listing Hydroplaning as a Contributing Cause, 1968 - 1973.

In the mid-1960s, the British began development of a device to measure the coefficient of friction of an airfield pavement. The results of this development work was the Mu-Meter, a small trailer unit designed to furnish a continuous graphical record of the coefficient of friction developed between two toed-out wheels and the pavement surface. It remained to be shown, however, how this device could be effectively used to predict potential problems of skidding or hydroplaning.

In 1968, the National Aeronautics and Space Administration (NASA) developed a promising skid-resistance measuring device, the Diagonally Braked Vehicle (DBV). Early tests indicated a relationship between the wet-to-dry stopping distance ratio of this vehicle to a similar ratio for aircraft. In 1969 and 1970, the USAF participated with NASA in a project called "Combat Traction." An instrumented C-141 aircraft was landed at a number of airfields, and simultaneous measurements were made with the DBV and James Brake Decelerometer. The test program showed the James Brake Decelerometer was unreliable on wet runways. The DBV, on the other hand, showed promise as a measuring device (ref 1).

In 1970, the Civil Engineering Research Division of the Air Force Weapons Laboratory (AFWL), located at Kirtland AFB, NM, undertook research to develop a skid resistance system to accurately evaluate runway skid resistance/hydroplaning characteristics. This research was aimed toward evaluating available and promising systems and development of a standard procedure for making measurements.

Also in 1970 AFWL started research aimed at optimizing corrective techniques to be used on runway surfaces with poor skid resistance properties. This report summarizes the results of these two research efforts, both of which were completed in June 1974.

SECTION II

THE AFWL SKID RESISTANCE EVALUATION SYSTEM

During the time period 1970 - 1973, an active research program in skid resistance was conducted by the Civil Engineering Research Division of the Air Force Weapons Laboratory. This research was aimed toward two main objectives:

a. Development of a skid-resistance evaluation system which could be used to evaluate the skid-resistance/hydroplaning characteristics of any runway surface.

b. Development of optimum skid-resistant surface treatments for use on airfield pavements with poor skid-resistance properties.

This section will discuss briefly the results of research aimed toward the first objective; the following section covers work on objective 2.

1. GENERAL

The standard skid-resistance evaluation test development by AFWL is described in detail in AFWL-TR-73-165 (ref 2). A brief description of the test equipment and procedures is provided for convenience here.

2. TEST EQUIPMENT AND PROCEDURES

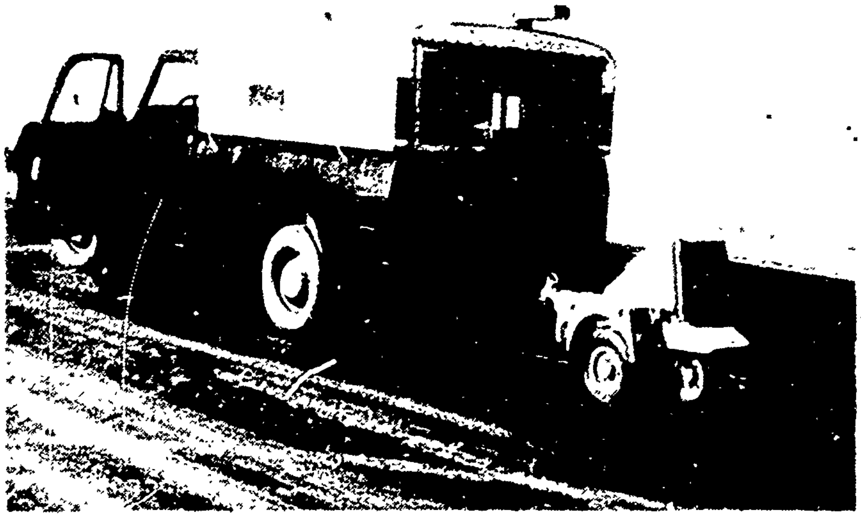
In the standard skid-resistance test developed at AFWL, the skid resistance/hydroplaning characteristics of the runway surface are evaluated by two types of test equipment: the Mu-Meter and the diagonally-braked vehicle (DBV). These two devices are shown in figure 2. The test program consists of field measurements of the pavement skid resistance/hydroplaning potential under dry and standardized artificially wet conditions. In addition, transverse slope measurements are conducted in the wheel paths on each side of the runway centerline to evaluate the surface drainage characteristics.

3. EQUIPMENT

The principal items of field testing equipment consist of the Mu-Meter, the diagonally braked vehicle, tank truck for water application, and a device for the measurement of the slope of the pavement surface.

(a) The Mu-Meter is a small trailer unit designed and manufactured by

MU-METER



DIAGONALLY-BRAKED VEHICLE (DBV)

Figure 2. Mu-Meter and DBV Tested by AFWL

M. L. Aviation (Maidenhead, Berks, England) for the specific purpose of evaluating coefficient of friction (Mu) for runway surfaces. The Mu-Meter phycically evaluates the side-slip force between the tires and pavement surface. It is a continuous recording device that graphically records the coefficient of friction (Mu) versus distance along the pavement. This system is also equipped with instrumentation which integrates the "Mu versus distance" curve to obtain the average coefficient of friction for selected areas within a test run. The friction measuring wheels are designed with 10 psi tires so that the test vehicle, when towed at 40 mph, gives a speed equivalent to 1.2 times the theoretical hydroplaning speed (33 mph).

(b) The DBV is a specially designed and highly instrumented vehicle which was developed to evaluate the stopping characteristics of runway surfaces. The AFWL version is in a station wagon configuration. The DBV concept was developed by NASA in the Combat Traction Program (ref 1). The DBV records the stopping distance of the vehicle from 60 mph in a locked wheel mode under a diagonally braked configuration. Instrumentation in the vehicle records velocity and stopping distance.

(c) A water truck is normally furnished by the fire department at the base tested. It must be equipped with a spray bar for water application, a fifth wheel or tachometer for precise speed measurements, and a constant pressure discharge system. The water is applied to two passes. The truck must be very carefully calibrated so that each pass places 0.1 inch of water on the test strip. Testing follows immediately after the second pass.

(d) The slope measuring device consists of a rectangular section of aluminum (10-ft long, 5/8-in thick, and 2-1/2-in high) with machinists levels attached so as to define slopes from 0 to 2.0 percent to the nearest 0.1 percent. The slope measuring device is used to measure transverse gradients in the wheel path areas.

4. TESTING PROCEDURE

The field test procedure used for the evaluation of the skid resistance/hydroplaning characteristics of the runway surface is outlined briefly below:

(a) Five to seven test areas (8 ft by 2000 ft) are selected as a representative sampling of the entire runway surface (see figure 3). Test sections are selected to examine the pavement traction in (1) the aircraft touchdown areas, (2) the runway interior in the major traffic paths where

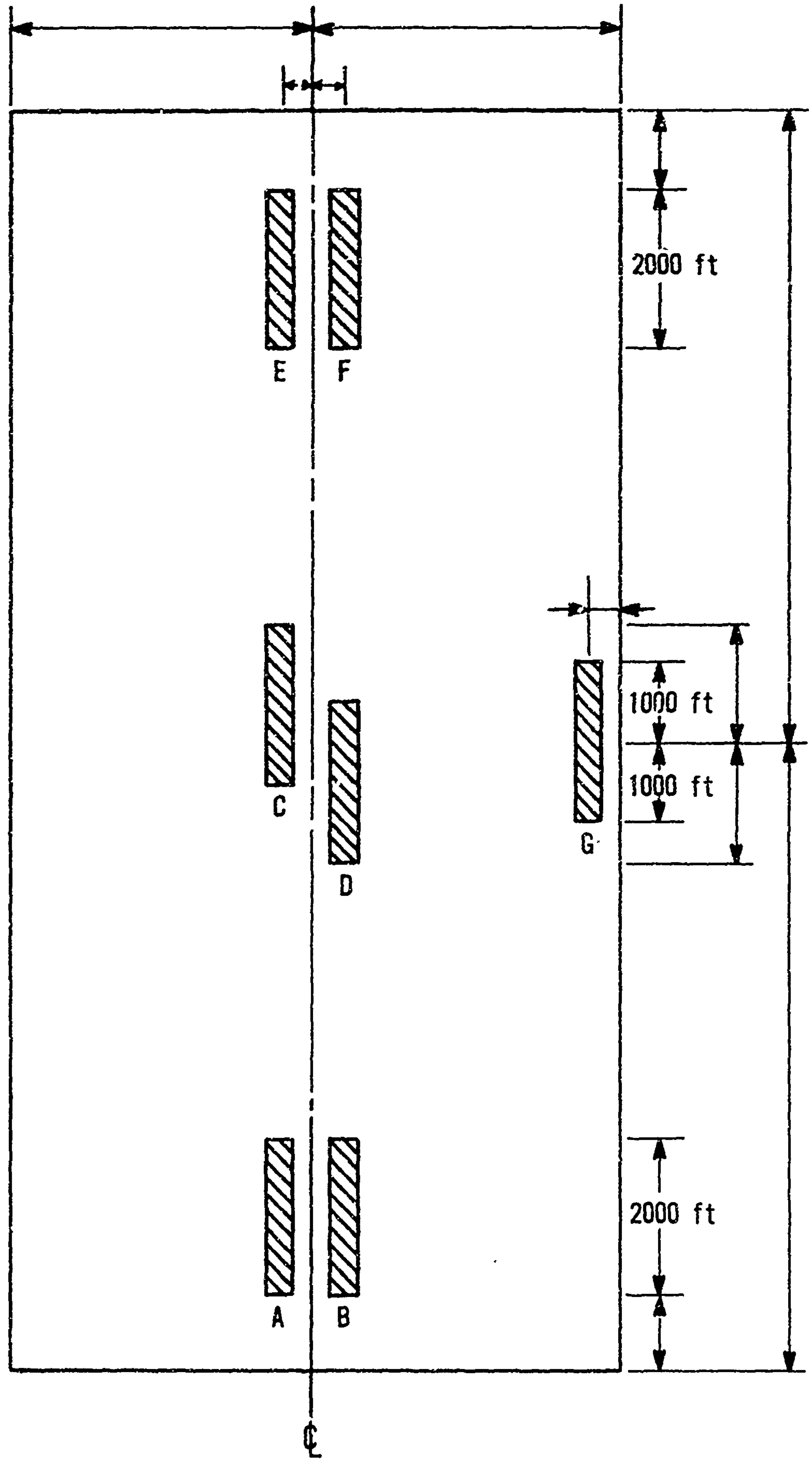


Figure 3. Layout of Test Strips

maximum braking is normally developed, and (3) the pavement edge which is representative of nontraffic areas.

(b) Transverse slope measurements are conducted at 500- or 1000-ft intervals in the wheel path areas on each side of the runway centerline.

(c) The water truck is precisely calibrated to discharge 0.1 inch of water.

(d) The skid resistance test for the dry pavement condition is conducted using the DBV and Mu-Meter. The pavement surface in each test area is evaluated in both directions.

(e) Skid resistance tests under a standardized artificially wet condition are conducted:

(1) Water is applied to the test area in two passes, each pass places 0.1 inch of water.

(2) DBV and Mu-Meter tests are conducted immediately following the second pass of the water truck. From 8 to 10 Mu-Meter and 6 to 8 DBV tests are conducted in each test area. (Tests are continued for up to one hour after wetting.) Half the tests are conducted in each runway direction.

(3) All water truck, Mu-Meter, and DBV operations are recorded versus time to the nearest second, using stop watches. The sequence of operations is controlled by radio.

5. TEST RESULTS

The pavement skid resistance results are reported in terms of the coefficient of friction (Mu), as measured by the Mu-Meter, and the wet-to-dry stopping distance ratio (SDR), as measured by the diagonally braked vehicle. Research at the Weapons Laboratory has indicated breakpoints in the values of Mu and SDR which define potential hydroplaning problems; these breakpoints are shown on the rating charts in table 1. These rating charts were developed from the results of the AFWL research program and the Joint NASA/FAA/AF test program with actual aircraft; the development of the charts is described in Appendix A. While the current state-of-the-art prevents a more precise delineation of exact aircraft responses, the charts provide a good rule of thumb for interpretation of data.

6. FRICTION OF RECOVERY WITH TIME

In figure 4, the effect of time after wetting (inverse of water depth) on changes in surface friction is shown for three areas of a typical runway. This chart demonstrates the natural drainage characteristics of the runway surface and the time required for the friction in the regions shown to return to a dry

Table 1. MU-METER AIRFIELD PAVEMENT RATING

Mu	Expected Aircraft Braking Response	Response
Greater than 0.50	Good	No hydroplaning problems are expected.
0.42 - 0.50	Fair	Transitional.
0.25 - 0.41	Marginal	Potential for hydroplaning for some aircraft exists under certain wet conditions.
Less than 0.25	Unacceptable	Very high probability for most aircraft to hydroplane.

Table 2. STOPPING DISTANCE RATIO AIRFIELD PAVEMENT RATING

	Hydroplaning Potential
1.0 - 2.0	No hydroplaning anticipated.
2.0 - 2.5	Potential not well defined.
2.5 - 3.5	Potential for hydroplaning
Greater than 3.5	Very high hydroplaning potential.

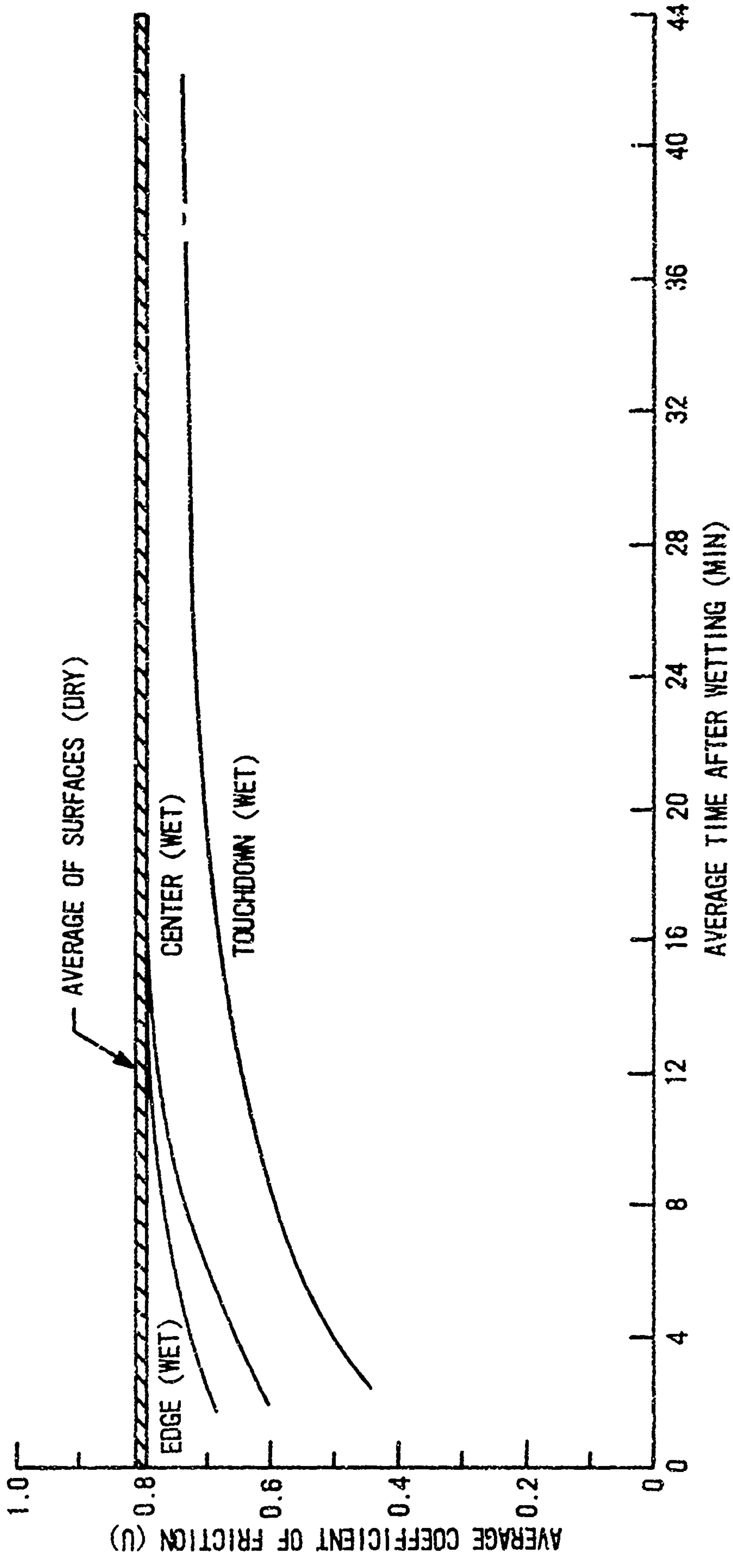


Figure 4. Surface Friction Recovery Versus Time After Wetting

pavement condition. These curves were derived by plotting the average coefficient of friction over the 2000-ft test sections versus time after wetting. The form of this relationship is well documented in reports of skid resistance testing at some 17 Air Force bases (refs 3-19). The curves suggest that the overall surface drainage is good and that the near dry conditions return relatively rapidly on this particular runway.

Figure 5 shows the relationship between stopping distance ratios and time after wetting for sections of a typical runway. Information gained from these curves is similar to that available from figure 4; in both cases friction characteristics recover quite rapidly as the pavement drains and dries.

7. FRICTION VARIATION

Figure 6 shows the actual friction versus distance trace as recorded by the Mu-Meter during the first test run after wetting for three areas of a typical runway surface. It shows the variation of friction within the 2000-foot test sections, and compares these results with the dry pavement condition. The sharp dips in the curves indicate some water ponding on the runway surface. This chart indicates that the central portion (longitudinally) of the runway has better skid resistance than the touchdown area, and the edge has the best skid resistance of all. (This is typical of most runways.)

8. TRANSVERSE SURFACE SLOPES

Table 3 shows typical information gained from transverse slope measurements. In this particular data set, it is easy to detect a potential ponding situation at the 4500-foot mark, where the surface slope reverses itself. If this reverse slope continued over several 500-foot intervals, it could indicate a location with high hydroplaning potential. The identification of such locations is extremely important to permit timely corrective action prior to an actual hydroplaning incident.

9. DATA REDUCTION PROGRAM

The Weapons Laboratory has developed an automated analysis program to process all data gathered in the standard test. Data are recorded on specially prepared forms designed in such a way that all information can be keypunched directly without recopying the field data (ref 2). Output from the analysis program includes summary charts showing the skid-resistance properties of each test section, and plotted curves showing the recovery of friction characteristics as each wetted test section drains and dries. Table 4 and figure 7 show examples of some of the

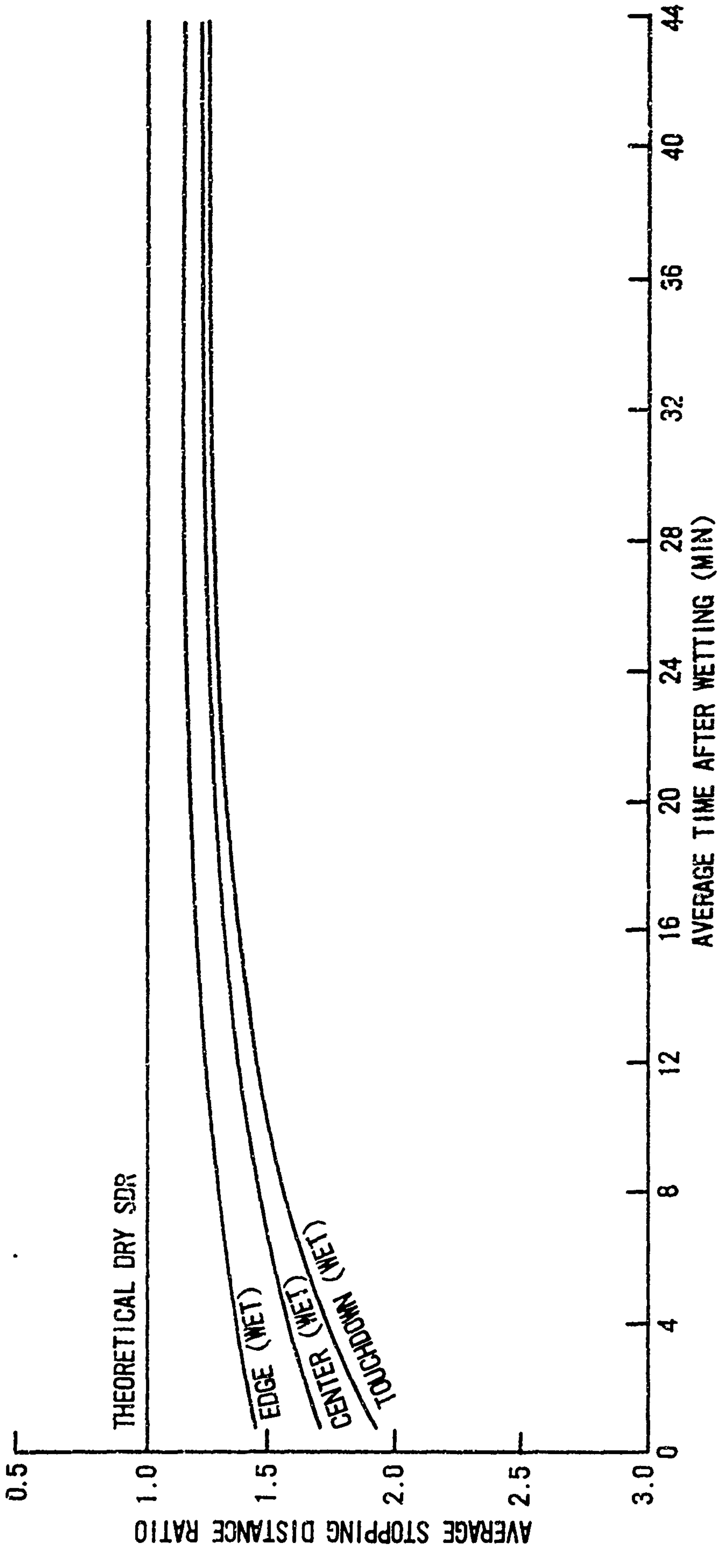
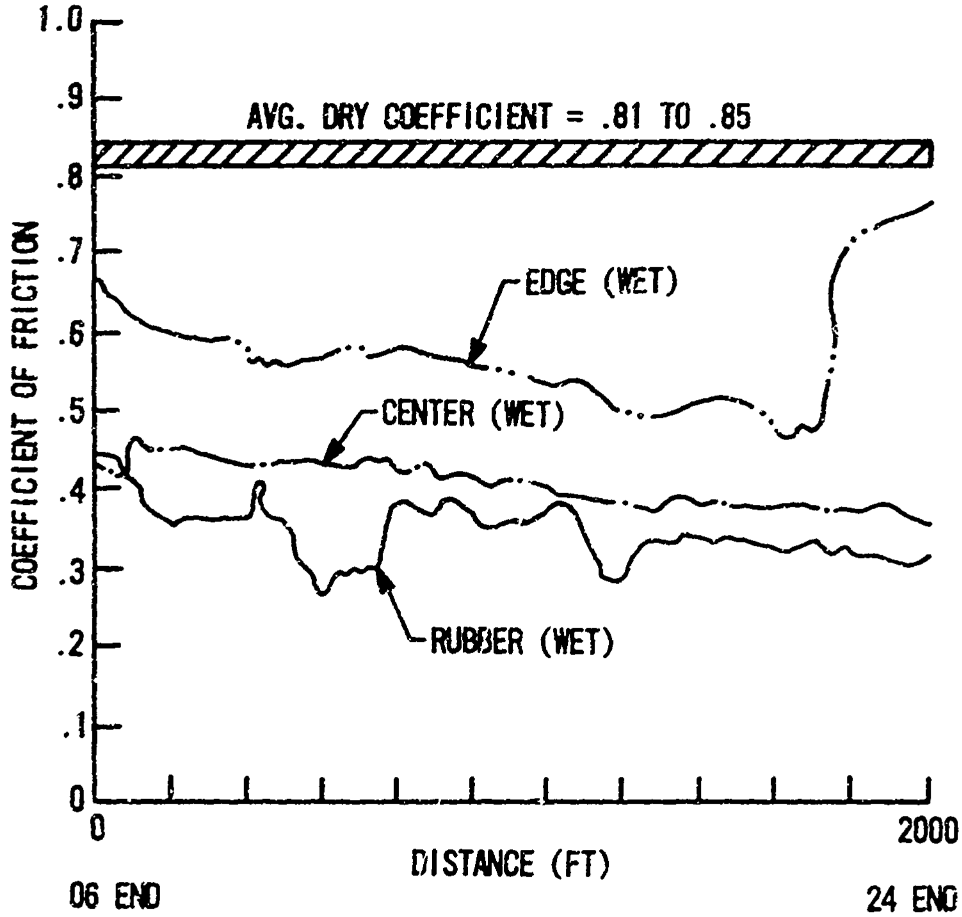


Figure 5. Stopping Distance Ratio Versus Time After Wetting



RUBBER AVG. MU = .34

CENTER AVG. Mu =.41

EDGE AVG. Mu = .55

Figure 6. Typical Mu-Meter Traces for Test Sections of the Pavement Surfaces at Wurtsmith AFB

Table 3

TRANSVERSE SLOPE MEASUREMENT

Distance From 26 End (Ft)	10' (%)	10' (%)	10' (%)	10' (%)
6000	0.6	0.8	1.4	1.1
5500	1.1	0.7	1.4	0.8
5000	0.7	1.3	1.1	0.9
4500	0.8	-1.1	0.8	0.9
4000	0.7	0.8	1.0	0.9
3500	1.1	0.9	0.9	1.8
3000	0.7	0.4	0.9	0.6
2500	0.6	1.2	1.4	1.3
2000	0.6	0.7	1.7	1.3
1500	0.6	1.1	1.1	1.4
1000	0.7	1.4	2.0	0.5
500	0.7	1.3	1.7	1.3
0	1.1	1.9	1.6	1.6

Table 4

SUMMARY OF SKID RESISTANCE CHARACTERISTICS, TEST AREA 00, RAF ALCOMBURY

TEST AREA	RUN NO.	SURFACE CONDITION	HEADING	MU-METER AVG TIME AFTER WET	MU-METER MU MIN	MU-METER MU MAX	MU-METER MU AVG(1)	AVG TIME AFTER WET	D R V WET STOP DIST	D R V DRY STOP DIST	SDR(2) 300
00	1	DRY	30				.74			461	
00	2	DRY	12				.77			525	
00	1	WET	30	2.00	.50	.64	.63	2.66	565		1.88
00	2	WET	12	3.43	.58	.72	.66	3.33	641		2.14
00	3	WET	30	4.7[illegible]	.58	.69	.68	4.87	491		1.64
00	4	WET	12	5.9[illegible]	.60	.74	.74	5.95	548		1.87
00	5	WET	30	7.38	.68	.74	.69	7.5[illegible]	491		1.64
00	6	WET	12	8.71	.69	.74	.69	8.72	527		1.76
00	7	WET	30	20.17	.68	.74	.69	25.76	424		1.41
00	8	WET	12	21.24	.69	.75	.72	27.08	477		1.59
00	9	WET	30	25.61	.66	.72	.69				
00	10	WET	12	27.32	.69	.82	.76				

(1) INTEGRATED COEFFICIENT FOR EACH TEST LANE
(2) COMPUTED USING DRY STOPPING DISTANCE OF 300 FEET

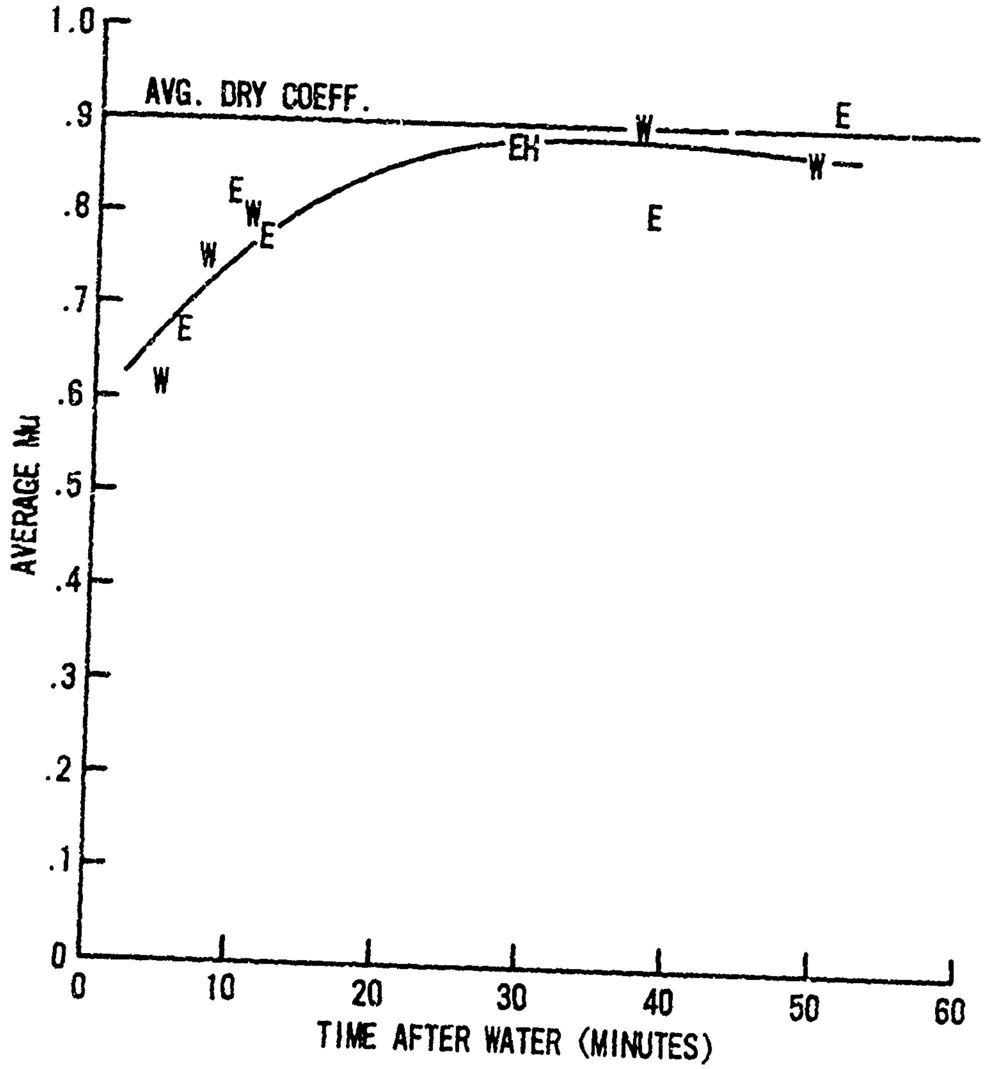


Figure 7. Plot Showing Recovery of Skid Resistance Characteristic as Pavement Dries, Test Section I, RAF Upper Heyford.

output from the automated analysis program. A special feature of the analysis package is that it also produces a written report in narrative form; the test conductor is required to provide only a layout drawing showing location of test sections and to write only a short discussion, the conclusions and any recommendations he wishes to make after examining the computer output. The computer program and its use are explained in AFWL-TR-74-180, (ref 20).

10. EQUIVALENT RCR VALUES

Because operational activities still use Runway Condition Readings (RCR), the Weapons Laboratory has adopted a method reported by NASA in Project Combat Traction for converting SDR values to equivalent RCR values, (ref 1). Figure 8 shows this relationship. The data analysis program makes the conversion from SDR values and prints out the approximate RCR value for the runway under wet conditions and under damp conditions. While the use of the relationship shown in figure 8 has not been proven reliable for every aircraft, it is the best means currently available for approximating an RCR value. AFWL research is continuing in this area; Appendix B contains the results of a study to verify the accuracy of this relationship for the F-4 aircraft, using data gathered during the F-4 Rain Tire Test Program (refs 21 and 22).

11. TEST LIMITATIONS

Work done to date at AFWL permits an excellent prediction and identification of runways with potential hydroplaning problems prior to the actual loss of an aircraft due to hydroplaning. However, actual stopping distance of aircraft cannot be predicted; this is particularly true when runway conditions fall below the breakpoints in table 1 or above the breakpoints in table 2 (potential hydroplaning) situations). However, the standard AFWL test will (1) determine if and where there is a potential hydroplaning problem on the runway, (2) determine, if the problem exists, how severe it is, (3) permit the base civil engineer to program improvements, and (4) give the pilot better indications of aircraft stopping performance.

Additional research is required to determine if both the Mu-Meter and the DBV are required in the evaluation program or whether one device is superfluous. At the present time, valuable information otherwise unavailable is gained from each individual piece of equipment. For this reason, the Weapons Laboratory chooses at this time to consider both a system for gaining an overall evaluation that neither could accomplish alone, and chooses not to rate one piece of

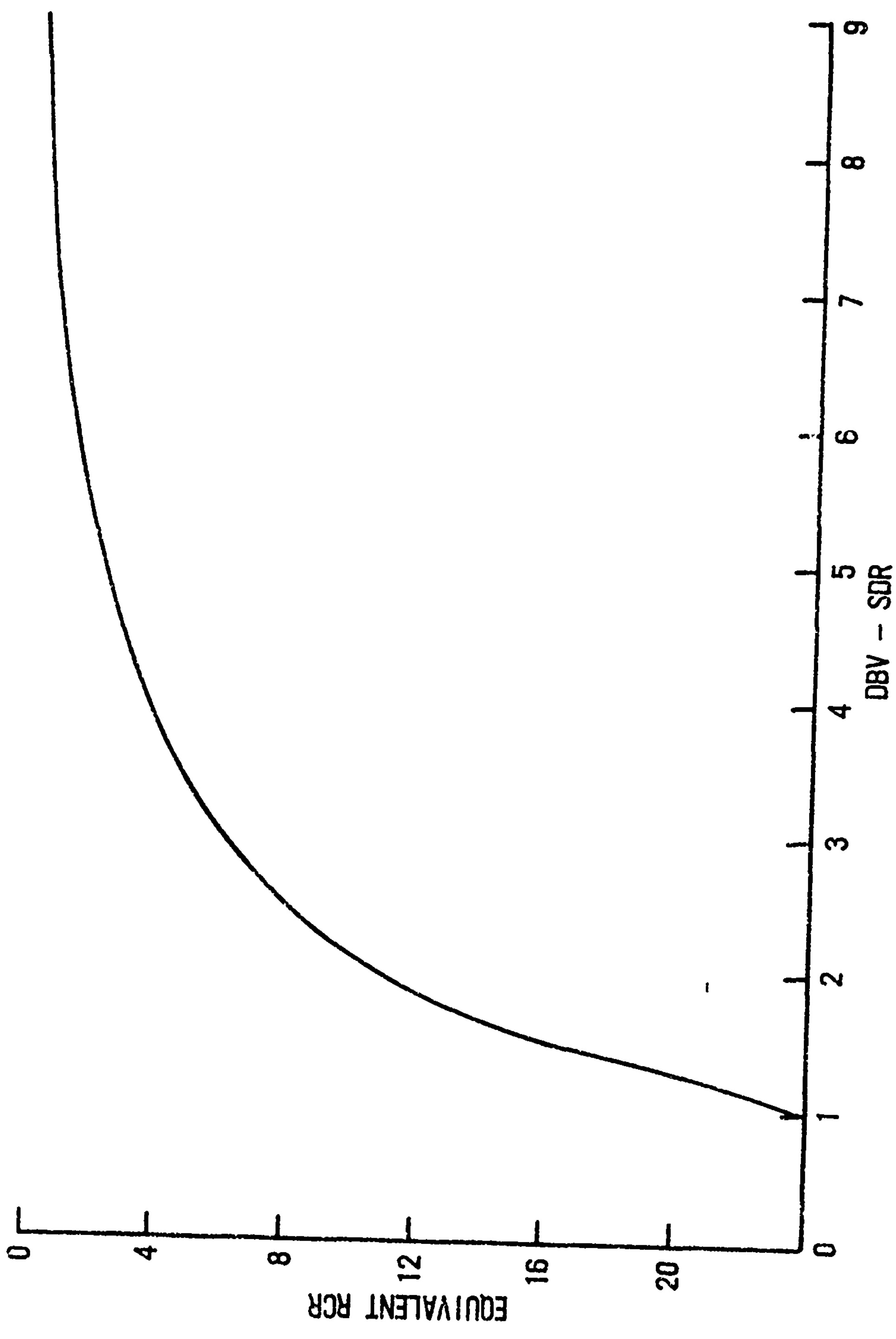


Figure 8. Theoretical Relationship Between DBV-SDR and Equivalent RCR. (After Ref. 1).

equipment above the other. Additional research may alter this approach, but certainly will not lessen the value of the information currently available from the two pieces of equipment used together.

Because only limited research has been done in developing a method to relate measured skid-resistance values to equivalent RCRs, the Weapons Laboratory is able to provide only a good approximation of what the RCR on a given runway should be. But since the James Brake Decelerometer has proven unreliable and inconsistent, and operational needs still dictate that an equivalent RCR be identified, the method proposed herein is currently the only way to arrive at an approximate value.

12. OPERATIONAL EVALUATION PROGRAM

Realizing the potential savings possible from an identification and corrective action program to prevent loss of multi-million dollar aircraft due to hydroplaning, the Air Force Civil Engineering Center undertook a worldwide skid-resistance evaluation program in FY74. The Center, located at Tyndall AFB, FL, established a skid-resistance evaluation team to perform the standard AFWL skid-resistance test at bases throughout the Air Force. AFWL transferred test equipment and written procedures to the Center and conducted an intensive training session to demonstrate for Center personnel the correct procedures for conducting the standard test. The Center plans to evaluate approximately 30 bases per year; with the current inventory of approximately 150 active USAF airfields, each USAF airfield can be evaluated on a five-year cycle.

SECTION III

RESEARCH ON ANTI-HYDROPLANING SURFACE TREATMENTS

Concurrent with research efforts to develop a skid resistance evaluation system for airfield pavements, the Air Force Weapons Laboratory undertook research to develop optimum skid resistant surface treatments. Development work done by the British in the 1960s pointed toward use of an open-graded asphalt surface treatment called porous friction surface (PFS). This surface is put down either on existing well-drained asphalt pavement or on a leveling course applied to existing asphalt or portland cement concrete pavement, and is normally laid to a thickness of 3/4 inch.

Using specifications obtained from the British and modifying them to test several types of asphalt and several aggregate sizes, AFWL constructed test strips of PFS on a seldom-used taxiway at Albuquerque International Airport in the fall of 1971. Figures 9 and 10 show two separate views of these test strips under construction. A detailed description of the make-up of each test strip is included in AFWL-TR-74-177, and will not be repeated here (ref 23).

These test strips were observed for environmental effects until June 1974; during the winter of 1972-1973, they were subjected to natural freeze-thaw cycles by the flooding of specially constructed dams on the pavement surface. No appreciable damage was observed as a result of environmental effects or as a result of the freeze-thaw action on any of the PFS test strips. A forthcoming AFWL technical report now under preparation will contain more detailed information about this aspect of the tests.

In the fall of 1972, AFWL assisted the Strategic Air Command and Pease AFB, New Hampshire, in the construction at Pease AFB of the first PFS surface treatment on an operational Air Force base in the continental United States. The technical specifications used in construction of the PFS treatment at Pease AFB are included in Appendix C, and Figure 11 shows a view of the pavement surface approximately one year after construction.

At the time of the preparation of this report, the PFS at Pease AFB had been subjected to two years of snow removal operations with essentially no damage to the pavement surface. Some cracking problems had been encountered,

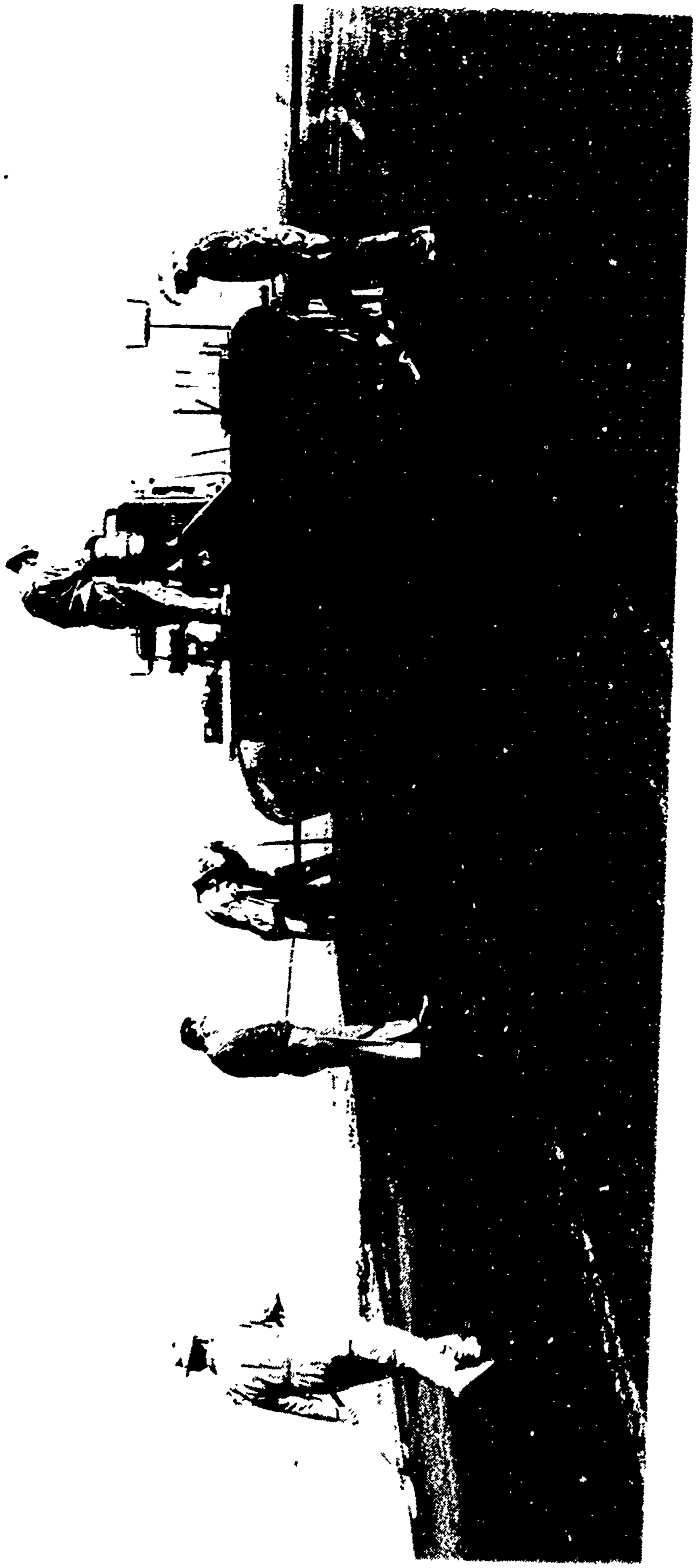


Figure 9. PFS Construction at Albuquerque International Airport, September 1971.

Figure 10. PFS Construction at Albuquerque International Airport Showing View of Some Completed Sections, September 1971.

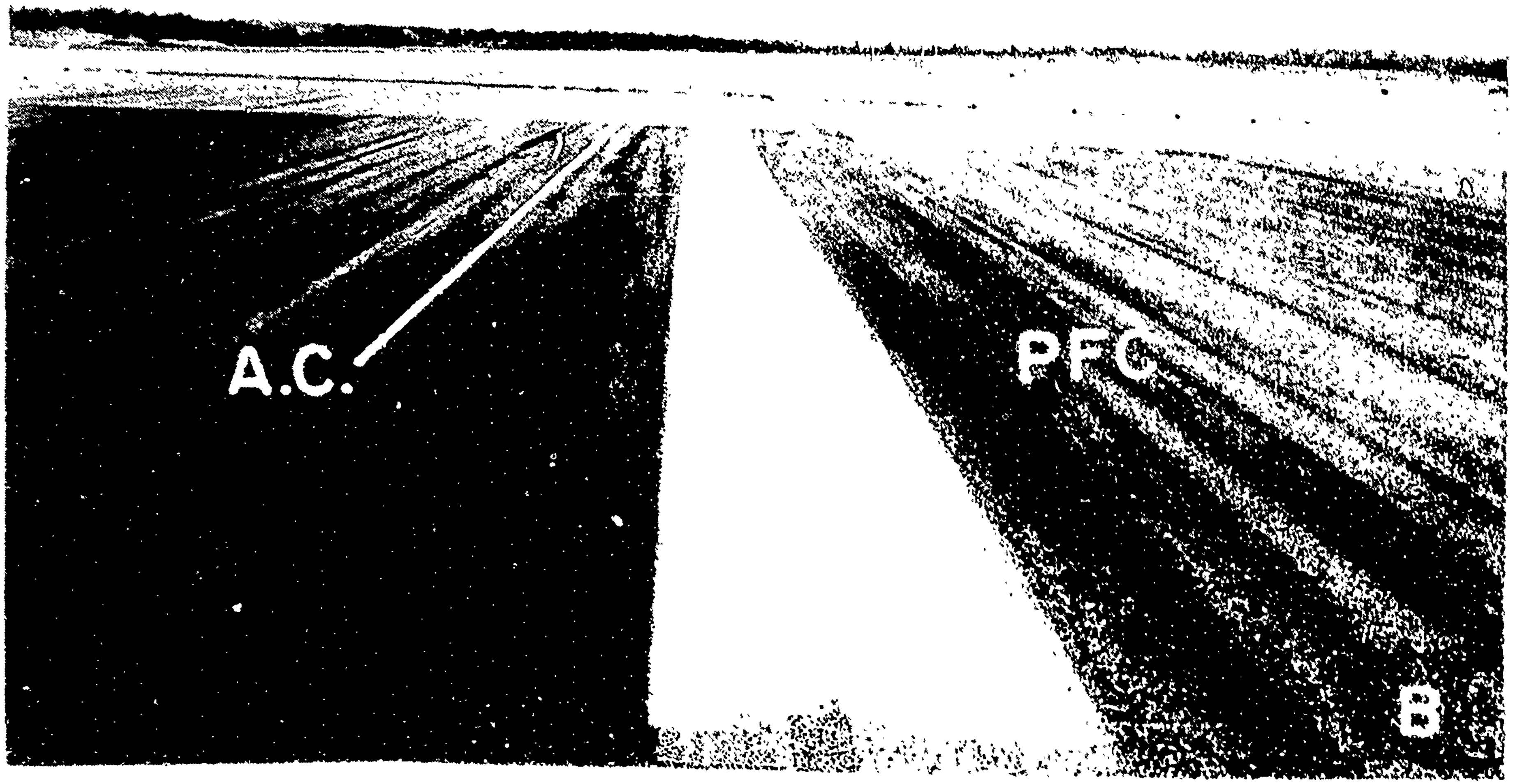


Figure 11. PFS Overlay at Pease AFB, NH, Approximately One Year After Construction (29 Oct 73).

however, and were mainly attributed to reflective cracking from the distress cracks in the old pavement surface. A thorough examination of these conditions was made by AFWL; Appendix D contains a letter report compiled as a result of this work. In general, the PFS surface at Pease AFB has performed well and no problems have been encountered which would discourage its use at other Air Force bases.

In search of additional antiskid overlay materials, AFWL constructed test strips (on both asphalt and concrete taxiway sections at Albuquerque International Airport) of four additional experimental materials in the fall of 1973. These materials were slurry seal, a flint aggregate resin combination with the trade name of Palmer Pavetread, a porous friction surface with emulsified asphalt, and a porous friction surface with 5 percent latex rubber added. The construction of these test sections is covered in detail in AFWL-TR-74-77, and will not be repeated here (ref 24).

In November 1973, the AFWL standard skid resistance test was conducted on these antiskid test sections, and all materials showed good skid resistance properties. The results of this test are reported in AFWL-TR-74-64 (ref 25). Freeze-thaw tests similar to those conducted on the PFS test strips were also conducted; figure 11a. shows the specially constructed dams used for this portion of the test. A separate technical report now under preparation will contain results of these tests.

In the spring of 1974, the PFS test strips constructed in 1971 and the experimental antiskid test sections constructed in 1973 were both subjected to load cart tests simulating F-4 and C-130 traffic. The details of this test will be published in a separate technical report now under preparation. As a result of the load cart tests, the following conclusions were reached about the antiskid materials tested:

a. Porous friction surface (PFS) performed extremely well as a surfacing material on asphalt pavements with adequate drainage. The data available did not conclusively prove what its performance on concrete would be.

b. Slurry seal did not meet the requirements for durability. Loose aggregate would present a constant threat to jet engines.

c. Palmer Pavetread failed to properly bond to asphalt pavement (apparently because of a chemical reaction between the two), and was unsatisfactory on portland cement concrete pavement because it chemically reacted with the joint sealer material. (See figure 11b.)

Figure 11a. View Showing Specially Constructed Dams Used in Freeze-Thaw Tests of Antihydroplaning Surfaces.

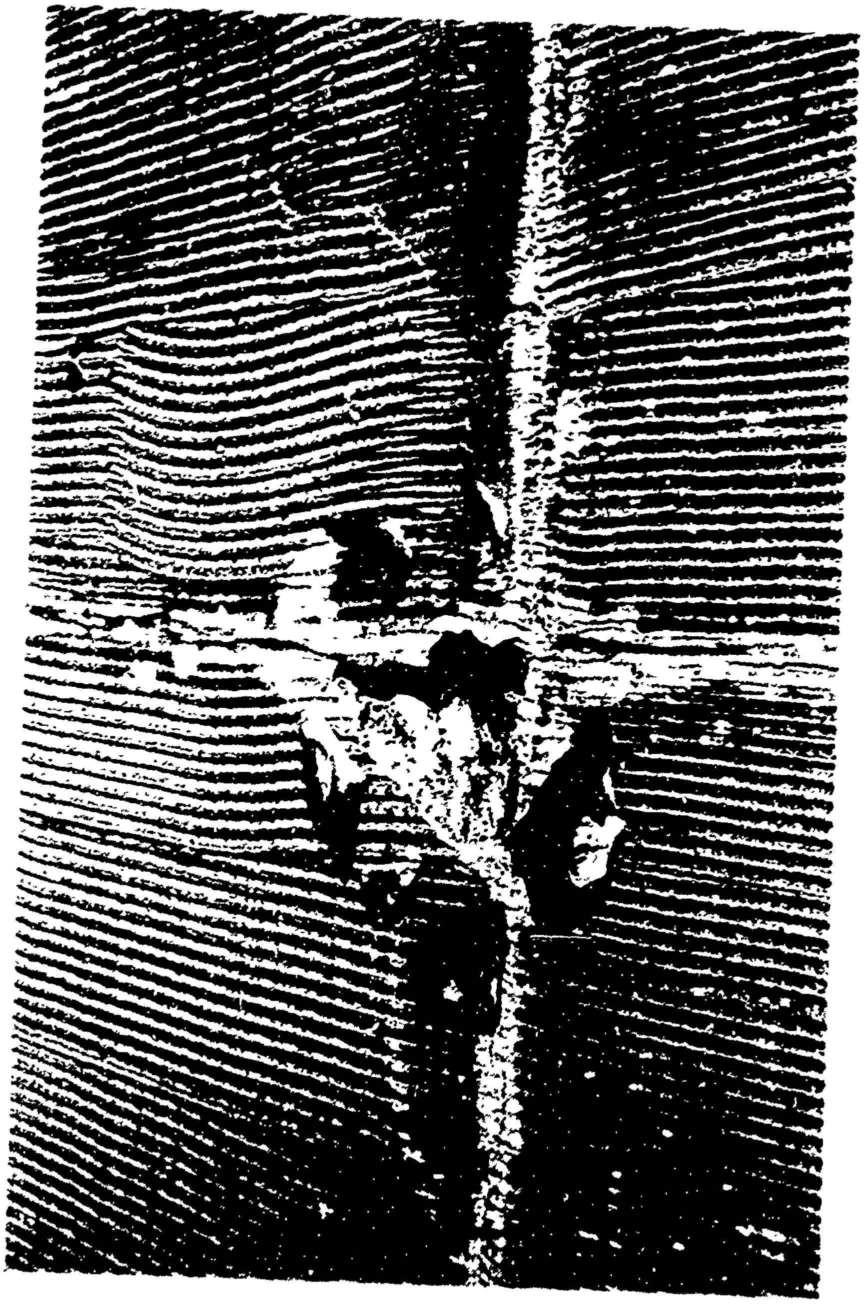


Figure 11b. View Showing Apparent Chemical Reaction Between Joint Sealer Material and Palmer Pavetread.

d. Porous friction surfaces constructed with emulsified asphalt did not meet the requirements for durability. Loose aggregate would be a constant problem.

e. Porous friction surface constructed with 5 percent latex rubber added performed very well as a surfacing on asphalt pavements. The use of this material appeared to hold great promise. Data available did not conclusively prove what its performance as an overlay on concrete would be.

As a result of the research done on antiskid materials, AFWL recommends consideration of the following treatments when it is necessary to improve the skid-resistance properties of an airfield pavement surface:

a. For an asphalt concrete pavement with adequate drainage and minimum cracking, application of a 3/4-inch porous friction surface.

b. For an asphalt concrete pavement with poor drainage or excessive cracking, application of a leveling course of asphaltic concrete followed by a 3/4-inch porous friction surface.

c. For a portland cement concrete pavement with adequate drainage, the sawing of transverse grooves in the areas of the runway where maximum braking is done.

d. For a portland cement concrete pavement with poor drainage, application of a leveling course of asphaltic concrete followed by a 3/4-inch porous friction surface.

For the use of any agency contemplating application of a porous friction surface, a set of guide specifications incorporating the results of all research done to date is included in AFWL-TR-74-177, (ref 23). These guide specifications represent the current state-of-the-art in PFS construction.

SECTION IV

THE EFFECT OF SNOW REMOVAL ON SKID RESISTANCE PROPERTIES

1. GENERAL

This section contains evidence supporting the theory that heavy snow and ice removal operations on portland cement concrete runways contribute significantly to lowering their skid resistance properties. This theory was formulated originally during examination of the runway surface at Griffiss Air Force Base, New York and discussions with snow removal personnel there where steel blades and tips set very low on the pavement surface have been used to remove snow and ice. Data supporting this theory were gathered by the Air Force Weapons Laboratory in their skid resistance tests conducted at a number of USAF bases in the US, principally bases of the Strategic Air Command. The theory is tested by examining coefficients of friction measured by use of the Mu-meter at different locations on the runway and comparison of these values between bases subject to varying amounts of snowfall.

2. ANALYSIS OF DATA FOR CONCRETE RUNWAYS

Figure 12 shows values of the coefficient of friction under dry conditions and under wet conditions at both the center and edge of concrete runways at seven bases which were tested. The "wet" coefficients of friction were measured three minutes after application of water to the surface in AFWL's standard procedure for testing skid resistance properties. Coefficients measured at the edge of the pavements simulate values for non-traffic areas and areas of little or no snow and ice removal, while those measured in the center of the runway correspond to areas with maximum traffic and maximum snow and ice removal effort. The seven bases were arranged in decreasing order of annual snowfall amounts.

To minimize the influence of outside factors which might obscure the effect of snow and ice removal operations (e.g., different original pavement textures, different field conditions, etc.) comparisons were made only between bases having nearly equal dry coefficients of friction and nearly equal wet coefficients of friction measured at the edge of the pavement. The data available provided two pairs of bases with widely varying amounts of snowfall for comparison: Griffiss with Grand Forks and Kincheloe with Minot. These comparisons are shown in table 5.

Base	Coefficient of Friction, Wet: Runway Center	Coefficient of Friction, Wet: Runway Edge	Coefficient of Friction, Dry	Average Annual Snowfall, Inches*
K. I. Sawyer	0.37	0.52	0.80	132.6
Griffiss	0.38	0.58	0.75	107.4
Kincheloe	0.39	0.63	0.83	110.0
Wurtsmith	0.43	0.56	0.80	57.0
Grand Forks	0.45	0.58	0.78	37.0
Minot	0.49	0.66	0.82	36.0
Altus	0.36	0.37	0.79	5.3

*Obtained from the weather detachment at each base.

Figure 12. Values of Coefficients of Friction on 7 Portland Cement Concrete Runways.

Table 5

COMPARISON OF FRICTION COEFFICIENTS VERSUS ANNUAL SNOWFALL

	Coefficient, Wet Center	Coefficient, Wet Edge	Coefficient, Dry	Average Annual Snowfall, Inches
Griffiss	0.38	0.58	0.75	107.4
Grand Forks	0.45	0.56	0.78	37.0
Δ Coefficients =	0.07			
=	15.6 %			
Kincheloe	0.39	0.63	0.83	110.0
Minot	0.49	0.66	0.82	36.0
Δ Coefficients =	0.10			
=	20.4 %			

There are a number of logical reasons why the differences shown above could occur:

a. Different construction techniques used to build the pavements and different ages of pavement. These factors are minimized by selecting for comparison those bases which have nearly equal dry coefficients of friction and nearly equal wet coefficients of friction measured at the pavement edge.

b. Large differences in the quantity or type of traffic. This effect is minimized by comparing only SAC bases.

c. Drainage of the runway center section. This reason is promptly discounted because all runways compared had excellent drainage and Griffiss AFB had the best of the four bases compared.

d. Experimental error due to test equipment and environmental variations. This could contribute some error, but the procedures used should hold this to an absolute minimum and certainly not of the magnitude of the differences shown above.

e. Polishing action of snow and ice removal equipment. By process of elimination, it is concluded this is the most significant factor contributing to the lower coefficients of friction at the bases having high snow and ice removal operations.

Additional evidence supporting this conclusion is shown in figures 13 and 14. Figure 13 shows the recovery with time of the coefficients of friction at the center and edge of the runways at Minot and Kincheloe. The two edge plots are very nearly identical while it takes approximately 30 minutes for the center plots to correspond. Since these plots are essentially a water depth relationship with time, and the smoother the surface the less water required for a low coefficient, the slower recovery rate for Kincheloe is indicative of a smoother surface.

Figure 14 shows the recovery with time of the coefficient of friction at Altus AFB, where very little snow removal occurs. Here the edge and center plots are in very close agreement.

3. SNOW AND ICE REMOVAL ON ASPHALT RUNWAYS

Data gathered on asphalt runways did not show trends indicating that snow and ice removal operations have a polishing affect such as is evident on concrete runways. This fact is attributed to the difference in material properties between the two systems. It is believed that snow and ice removal techniques tend to remove the surface texture on concrete surfaces, thus decreasing their skid resistance properties. The fact that portland cement concrete is affected while asphalt is not, is suspected to be due to the nature of the construction of each of them. In portland cement construction, a fine aggregate and mortar slurry tends to float to the surface, creating a thin layer with little wear resistance. In the case of asphalt, there generally exists a more uniform matrix throughout, and as the surface wears the fine aggregate and asphalt are removed, thereby exposing large aggregate with good skid resistance properties.

4. FINDINGS

The data discussed in this section support the contention that asphalt surfaces subjected to heavy snow and ice removal operations, would not be expected

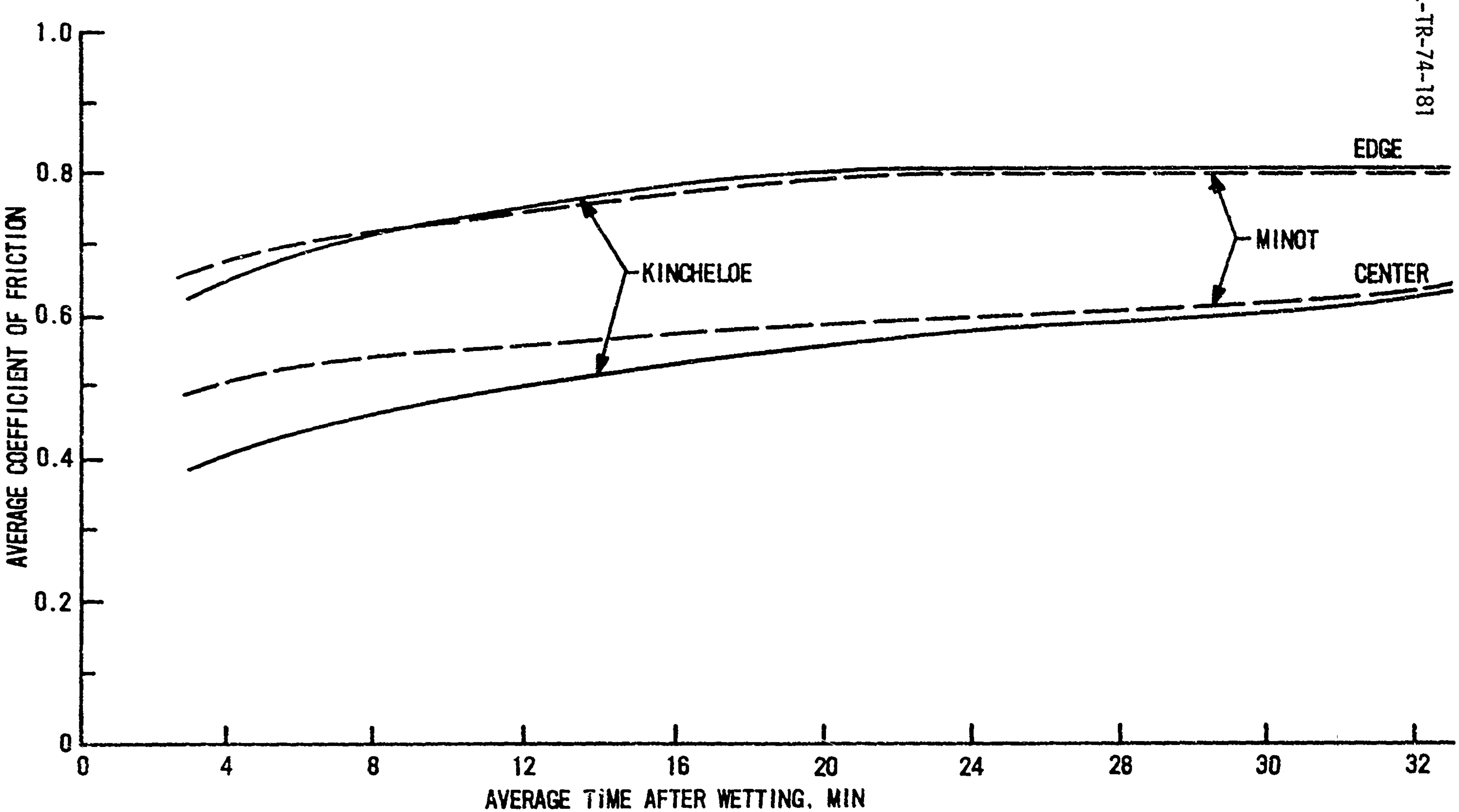


Figure 13. Friction Recovery with Time After Wetting Kincheloe and Minot AFB's

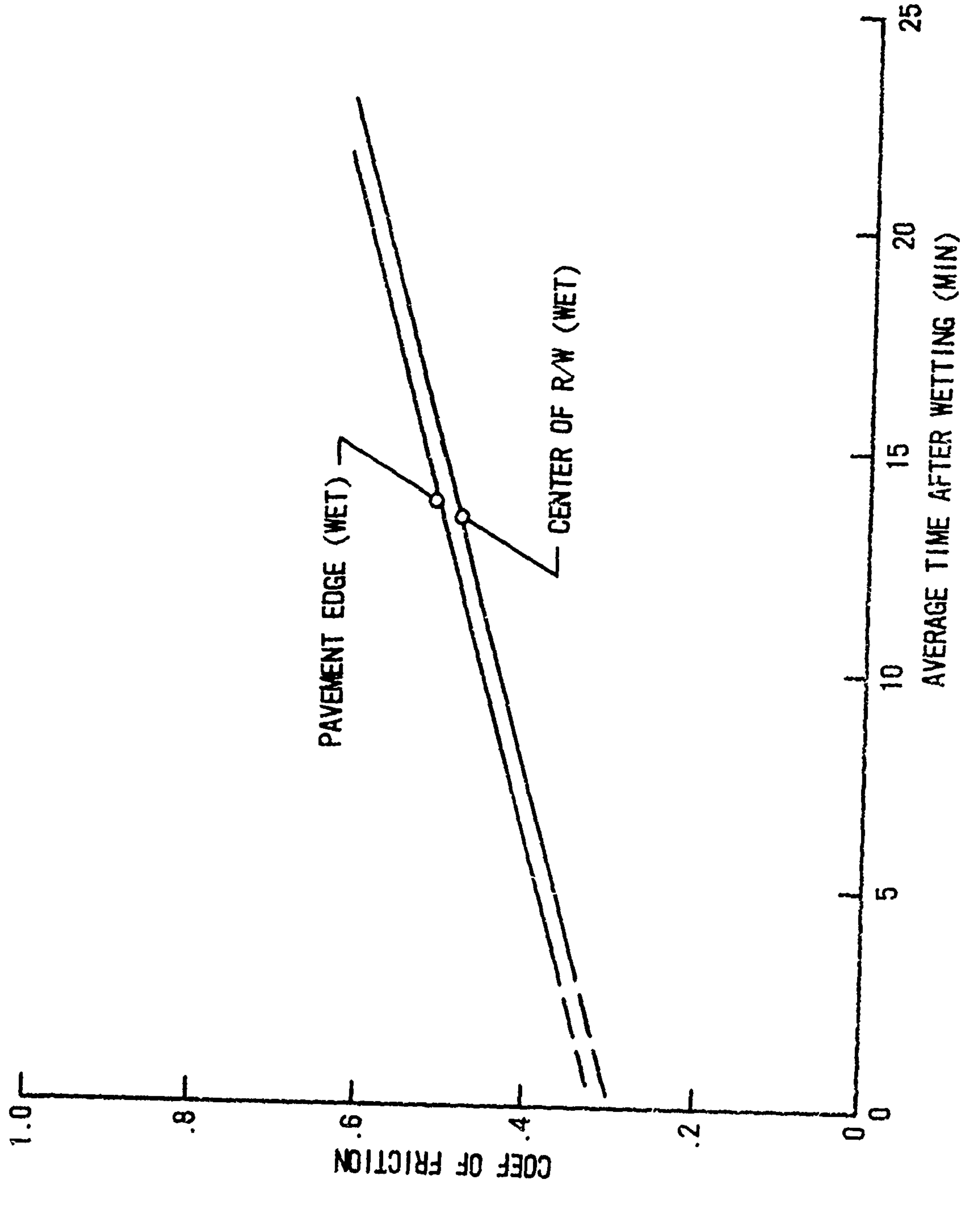


Figure 14. Friction Recovery with Time After Wetting, Altus AFB

to lose their good skid-resistance properties as rapidly as concrete surfaces. While this fact is not definitely and conclusively proven, the data available suggest that concrete runways subjected to heavy snow and ice removal operations should be checked frequently to insure their skid resistance characteristics remain acceptable.

SECTION V

RESULTS OF ANALYSES OF SKID RESISTANCE DATA

1. MU-METER/DIAGONALLY BRAKED VEHICLE CORRELATION STUDY

In an attempt to verify the consistency of the rating charts used to classify the hydroplaning potential of pavement surfaces in the AFWL Standard Skid Resistance Test, a study was conducted to check the degree of correlation between data gathered using the Mu-Meter and data gathered using the Diagonally Braked Vehicle. For the study, data gathered from a total of 14 bases were used. A list of the 14 bases is shown in table 6.

Table 6

LIST OF BASES USED IN CORRELATION STUDY

SAC Bases	Date Tested
Kincheloe AFB	12 Oct 72
Ellsworth AFB	21 Oct 72
Minot AFB	18-19 Oct 72
Wurtsmith AFB	10 Oct 72
Grand Forks AFB	17 Oct 72
European Bases	
RAF Upper Heyford	22 Nov 72
RAF Bentwaters	24 Nov 72
Zweibrucken AB	7-8 Nov 72
Spangdahlem AB	10 Nov 72
RAF Lakenheath	28 Nov 72
RAF Alconbury	20 Nov 72
RAF Woodbridge	26 Nov 72
Bitburg AB	12 Nov 72
Hahn AB	15 Nov 72

In all cases the data were gathered by following the procedures in the AFWL Standard Skid Resistance Test. The stopping distance ratio was "normalized" by

dividing the wet stopping distance by 300 feet, and the Mu-Meter value used was the integrated (or average) Mu determined by the quotient of C divided by B on the remote readout installed in the Mu-Meter towing vehicle.

A total of 596 data points were available for the correlation study; these data points were gathered on all types of pavement surfaces and at locations representing all typical runway traffic conditions. Table 7 shows how the data points were separated for detailed analysis, in an attempt to determine how the correlation between the Mu-Meter and Diagonally Braked Vehicle data varied on different surfaces.

Table 7

SURFACES STUDIED INDIVIDUALLY AND NUMBER OF DATA POINTS AVAILABLE FOR EACH SURFACE

Type of Surface	No. Points
Asphaltic Cement Concrete (ACC)	205
Portland Cement Concrete (PCC)	311
Porous Friction Surface (PFS)	80
ACC Touchdown Areas	90
ACC Central Areas	48
ACC Edge Areas	67
PCC Touchdown Areas	196
PCC Central Areas	46
PCC Edge Areas	69
PFS Touchdown Areas	48
PFS Central Areas	16
PFS Edge Areas	16
All Surfaces Together	596

2. RESULTS OF FIRST CORRELATION STUDY

Table 8 shows the simple correlation coefficients between the Mu-Meter and Diagonally Braked Vehicle data gathered on each of the surfaces, and that for all data combined. The table also shows the value of the stopping distance ratio (SDR) corresponding to a Mu-Meter value of 0.50, taken from the best fit least squares regression equation passed through the data points, using standard regression techniques on the CDC 6600 computer.

Table 8

RESULTS OF REGRESSION ANALYSIS

Type, Pavement	Simple Correlation Coefficient	Value of SDR at Mu = 0.50 on Plotted Curve
Asphaltic Cement Concrete (ACC)	0.6051	2.15
Portland Cement Concrete (PCC)	0.8432	2.70
Porous Friction Surface (PFS)	0.4882	No Data in Range
ACC Touchdown	0.3317	No Data in Range
ACC Center	0.5521	No Data in Range
ACC Edge	0.7863	2.25
PCC Touchdown	0.8272	2.85
PCC Center	0.8715	2.30
PCC Edge	0.8057	2.30
PFS Touchdown	0.5217	No Data in Range
PFS Center	0.6207	No Data in Range
PFS Edge	0.2530	No Data in Range
All Surfaces	0.8678	2.70

Several observations are possible from an examination of the simple correlation coefficients in Table 8. First of all, there appears to be a much better correlation between the Mu-Meter and Diagonally Braked Vehicle data on portland cement concrete pavement than on either asphaltic concrete or porous friction surface. It is interesting to note that the simple correlation coefficients are significant at the one percent level on all types of surfaces, with the exception of the porous friction surface edge strips.

The last column in Table 8 shows that the values of the stopping distance ratio (SDR) corresponding to a Mu-Meter friction reading of 0.50 (as read from the regression curves passed through all the points on that particular kind of surface) vary over a wide range. The average SDR value corresponding to a Mu-Meter reading of 0.50, as measured on the curve passed through all the data points, was 2.70. This would seem to indicate that a rating of "good" for a pavement surface with a stopping distance ratio of 2.00 or less, is somewhat conservative. Additional research and experience may indicate that it is appropriate to rate a pavement as "good" when it has an SDR somewhat larger than 2.00

Figure 15 through Figure 27 are plots of all the data studied, separated by type of surface and location of test sections, as shown in Table 8. In these particular plots, the Mu-Meter data were treated as the independent variable and the Diagonally Braked Vehicle data were the dependent. Curves passed through the data points were determined by least-squares methods on the CDC 6600 computer. In each case, 3 regression curves were determined and were plotted -- a linear curve, a second-order curve, and a third-order curve, and the particular plot shown in each of Figures 15 through 27 represent the "best-fit" for that particular set of data. The general form for the 3 regression equations were:

SDR = (Constant) + (Constant) (Mu)	Linear
SDR = (Constant) + (Constant) (Mu) + (Constant) (Mu^2)	Second Order
SDR = (Constant) + (Constant) (Mu) + (Constant) (Mu^2) + (Constant) (Mu^3)	Third Order

In every case the "best fit" for the data shown was represented by either the linear equation or the second-order equation, and these curves are thus the ones shown in figures 15 through 27, appropriately labeled to indicate the curve depicted.

3. RESULTS OF SECOND CORRELATION STUDY

A second study was conducted to verify the validity of an apparent correlation between Mu-Meter and Diagonally Braked Vehicle data gathered at the British Road Research Laboratory test tract and later in Sweden on snow and ice. The equation defining the relationship between the DBV and the Mu-Meter for this set of data (as reported by Mr. R. W. Sugg) was the following:

$$SDR = \frac{100}{(110)(Mu)^{1.5} + 16}$$

Figure 28 shows a plot of AFWL data adjusted to attempt duplication of the British results. Prior to plotting, the stopping distance ratio was divided into 100, and the Mu-Meter coefficient of friction was raised to the 1.5 power. A linear regression curve was then passed through all the data points, using a standard regression routine on the CDC 6600 computer. The equation of the line shown in figure 28 is:

$$SDR = \frac{100}{(84.29(Mu)^{1.5} + 8.87}$$

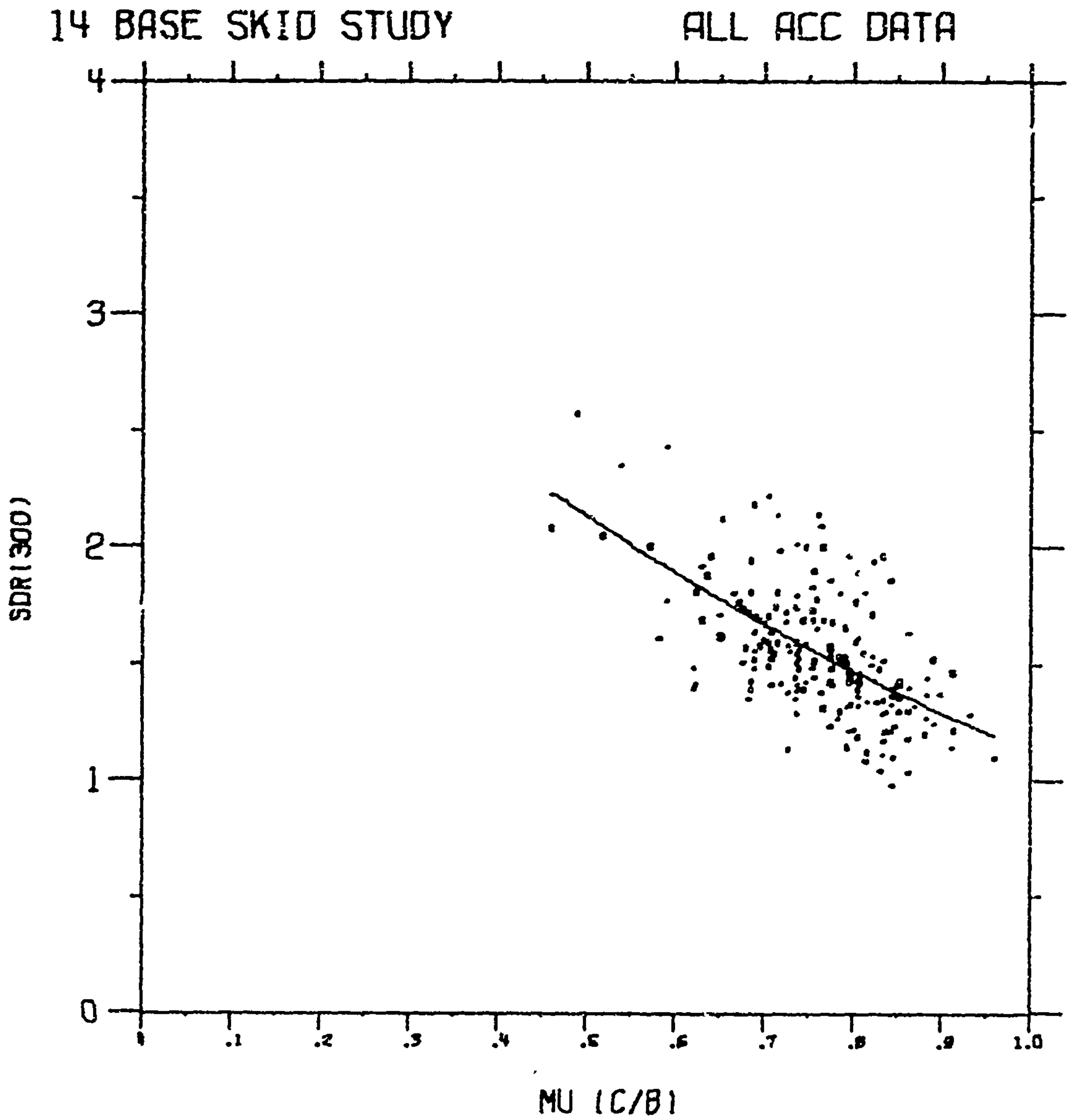


Figure 15. Mu-Meter Versus DBV Data on ACC Pavement (Second Order Curve Fit).

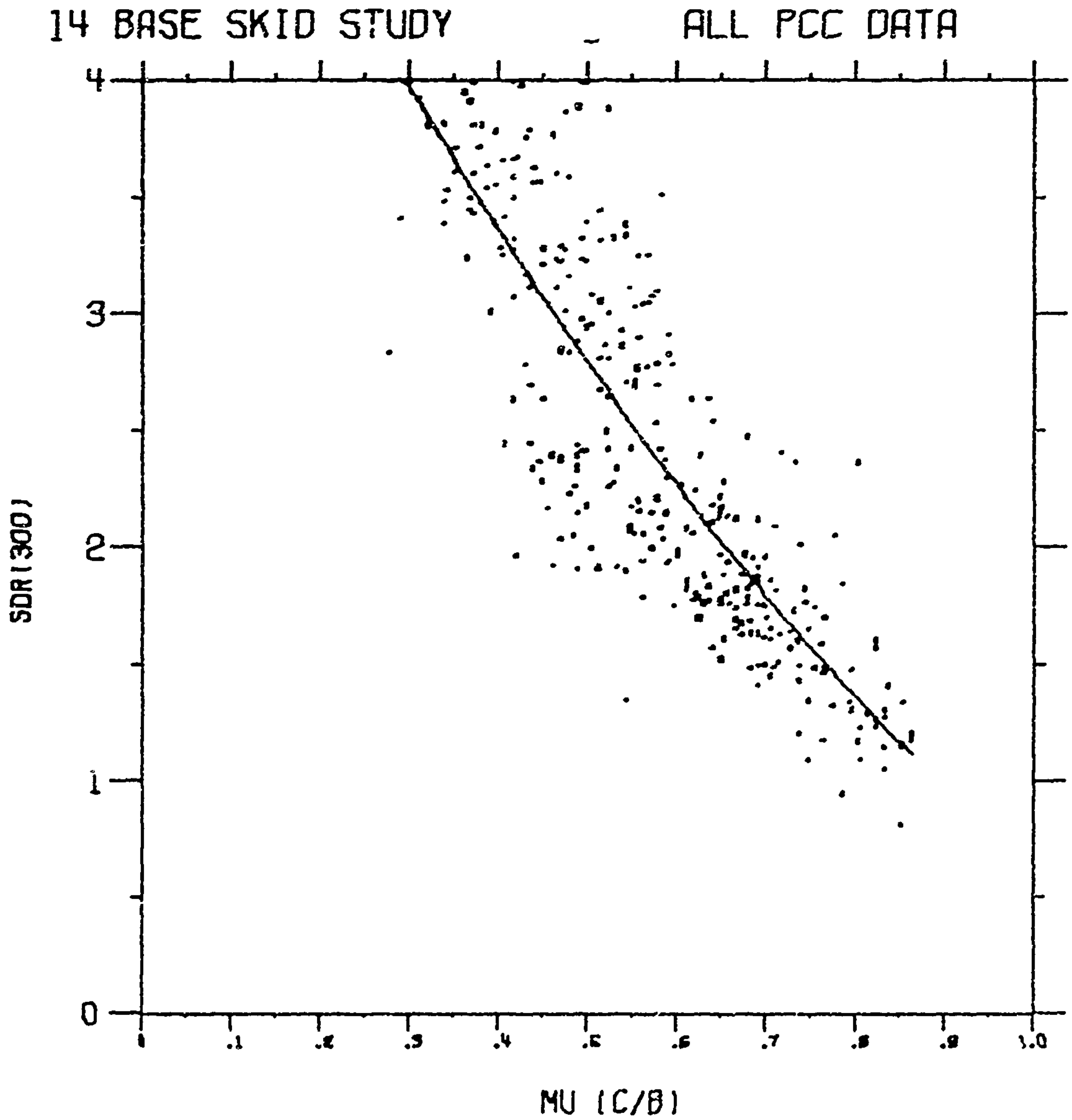


Figure 16. Mu-Meter Versus DBV Data on PCC Pavement (Second Order Curve Fit).

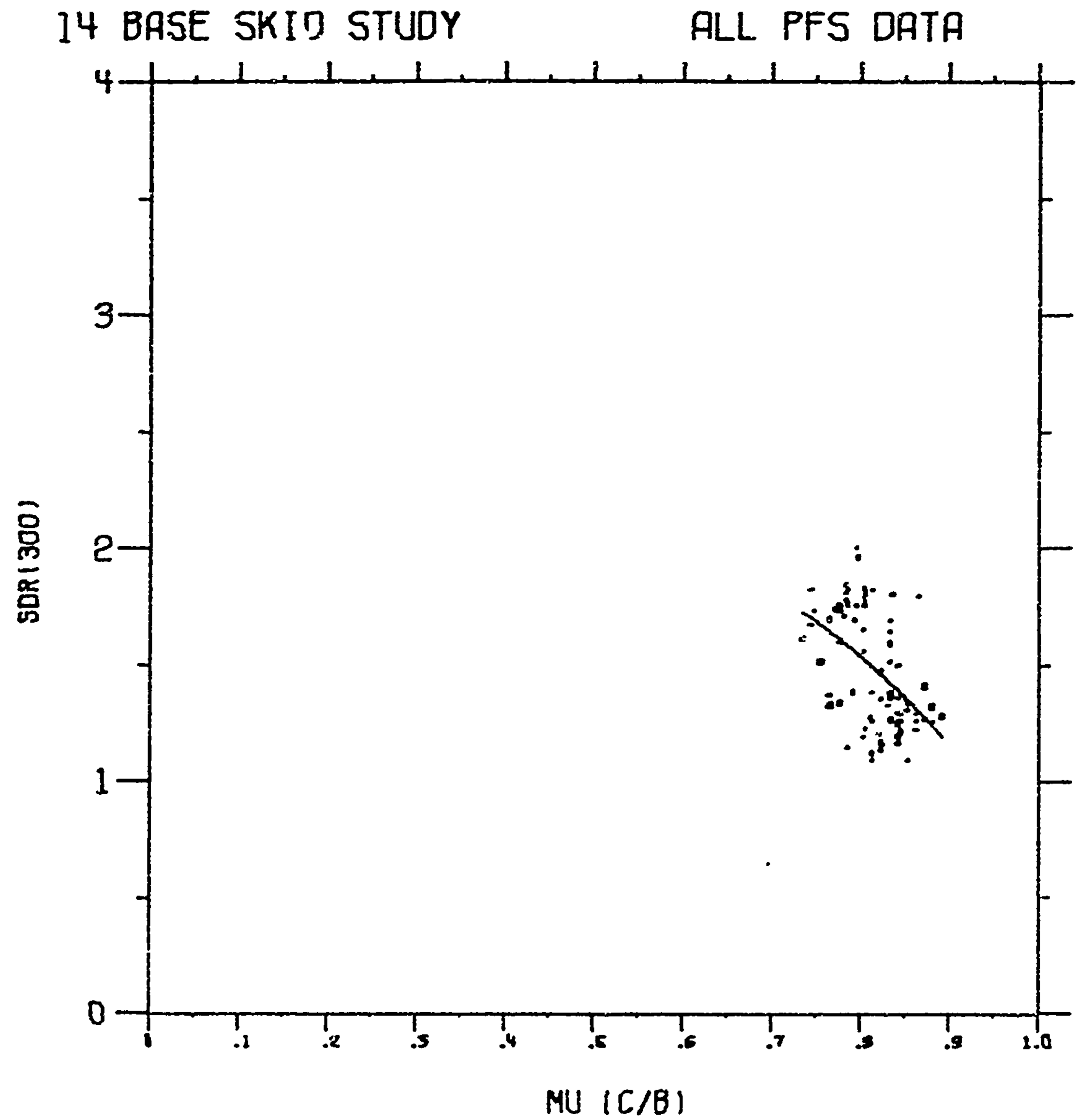


Figure 17. Mu-Meter Versus DBV Data on PFS Pavement (Second Order Curve Fit).

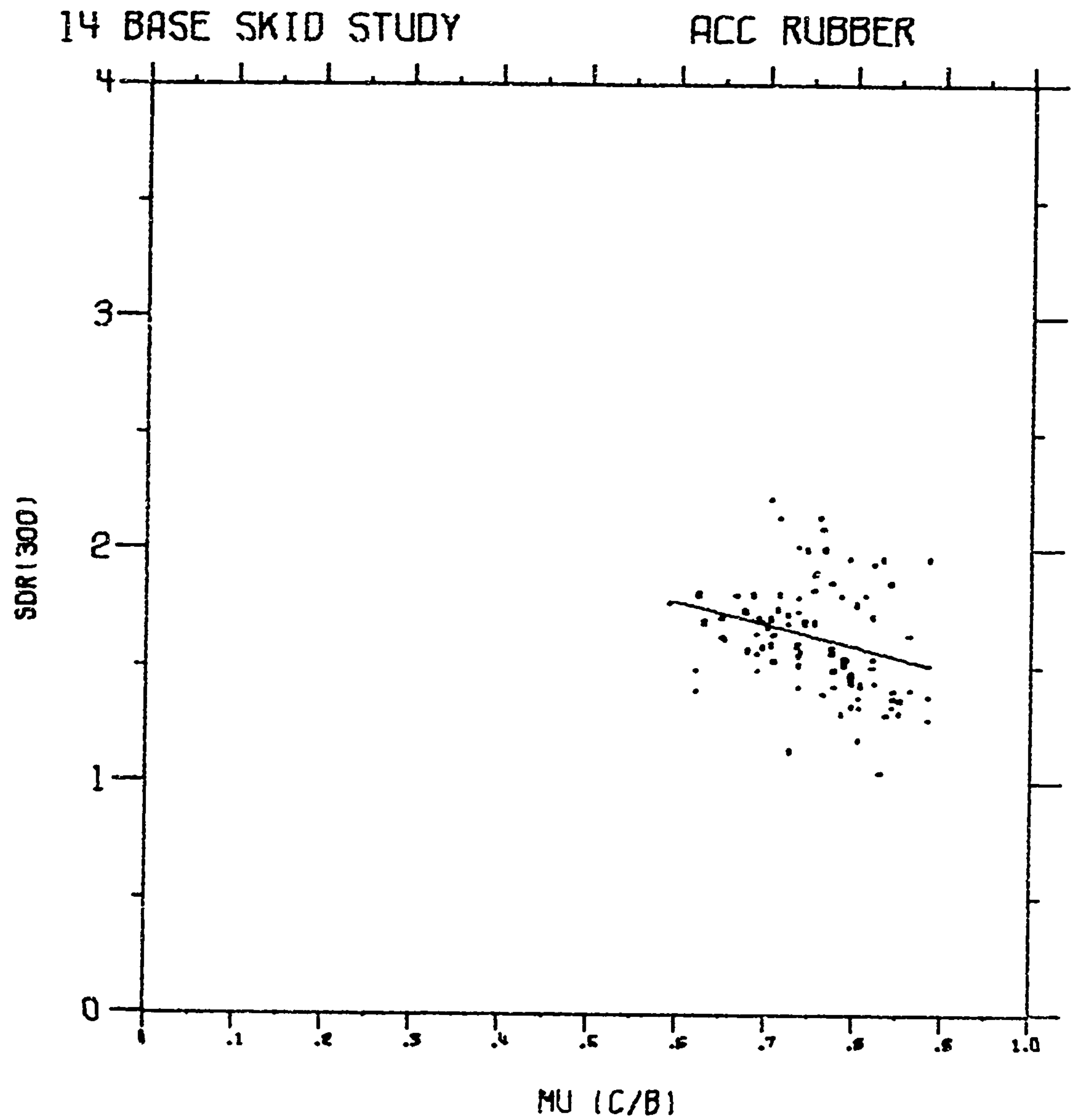


Figure 18. Mu-Meter Versus DBV Data on ACC Rubber Areas (Linear Regression Curve).

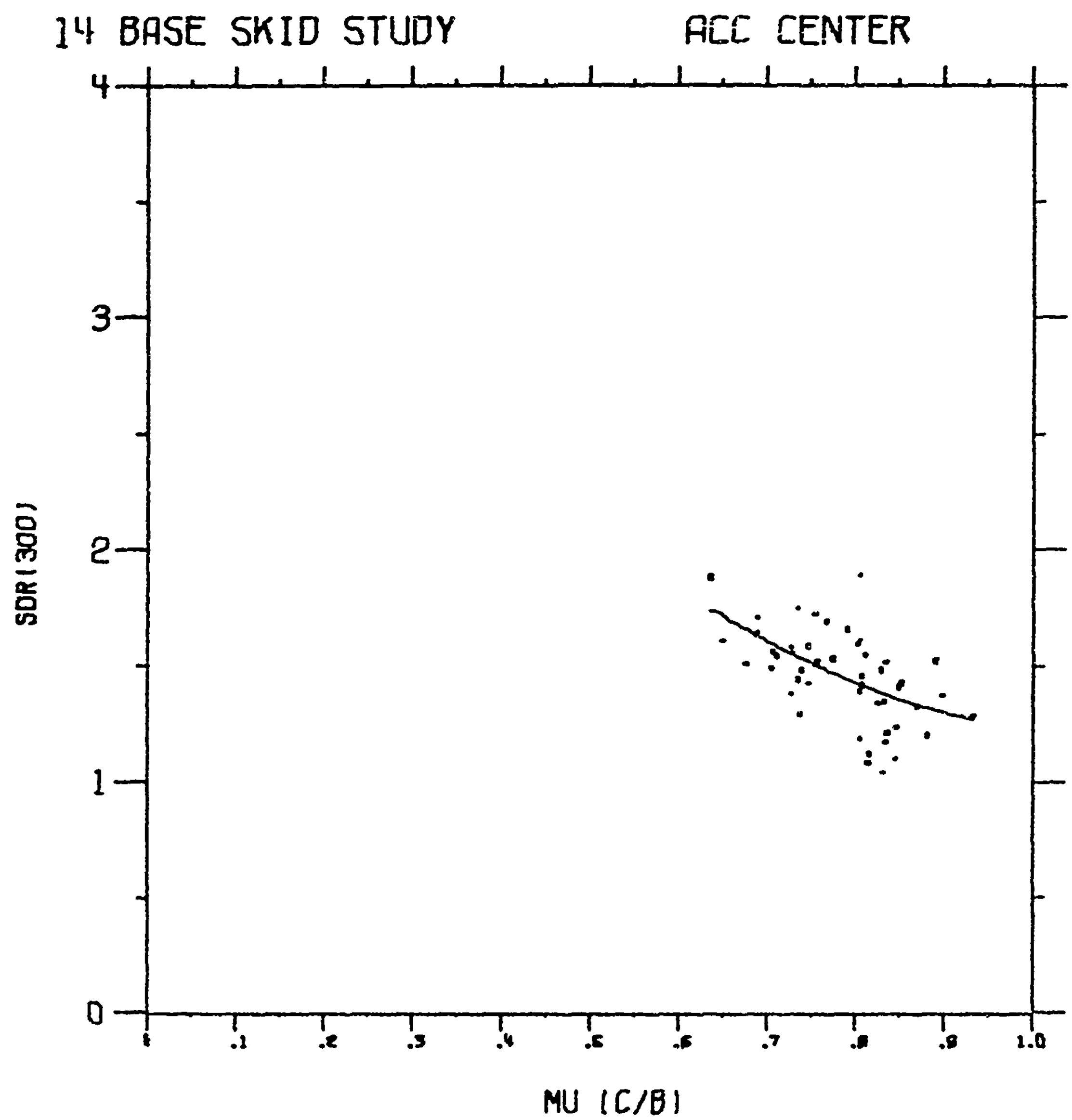


Figure 19. Mu-Meter Versus DBV Data on ACC Central Areas (Second Order Curve Fit).

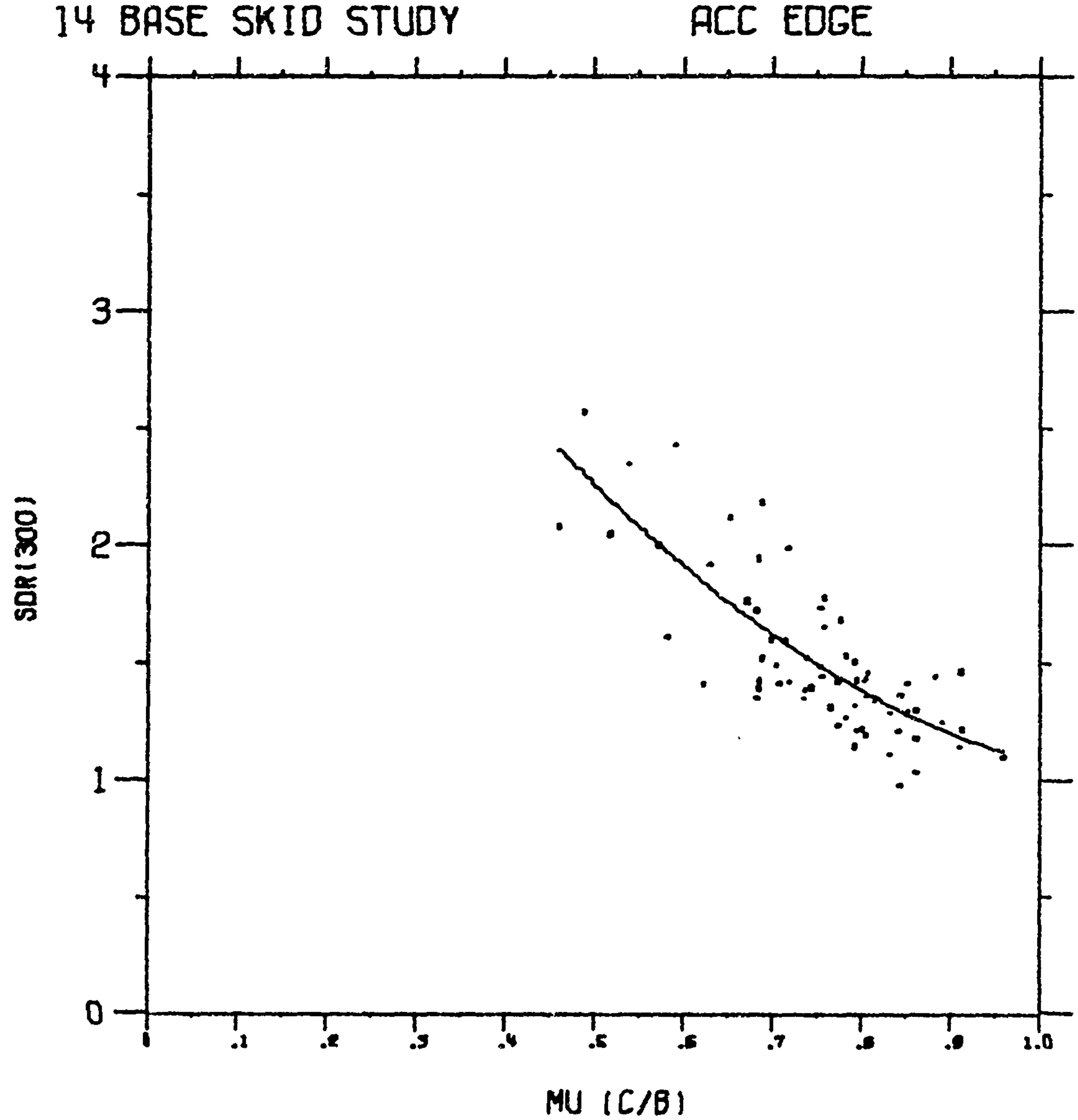


Figure 20. Mu-Meter Versus DBV Data on ACC Edge Areas (Second Order Curve Fit).

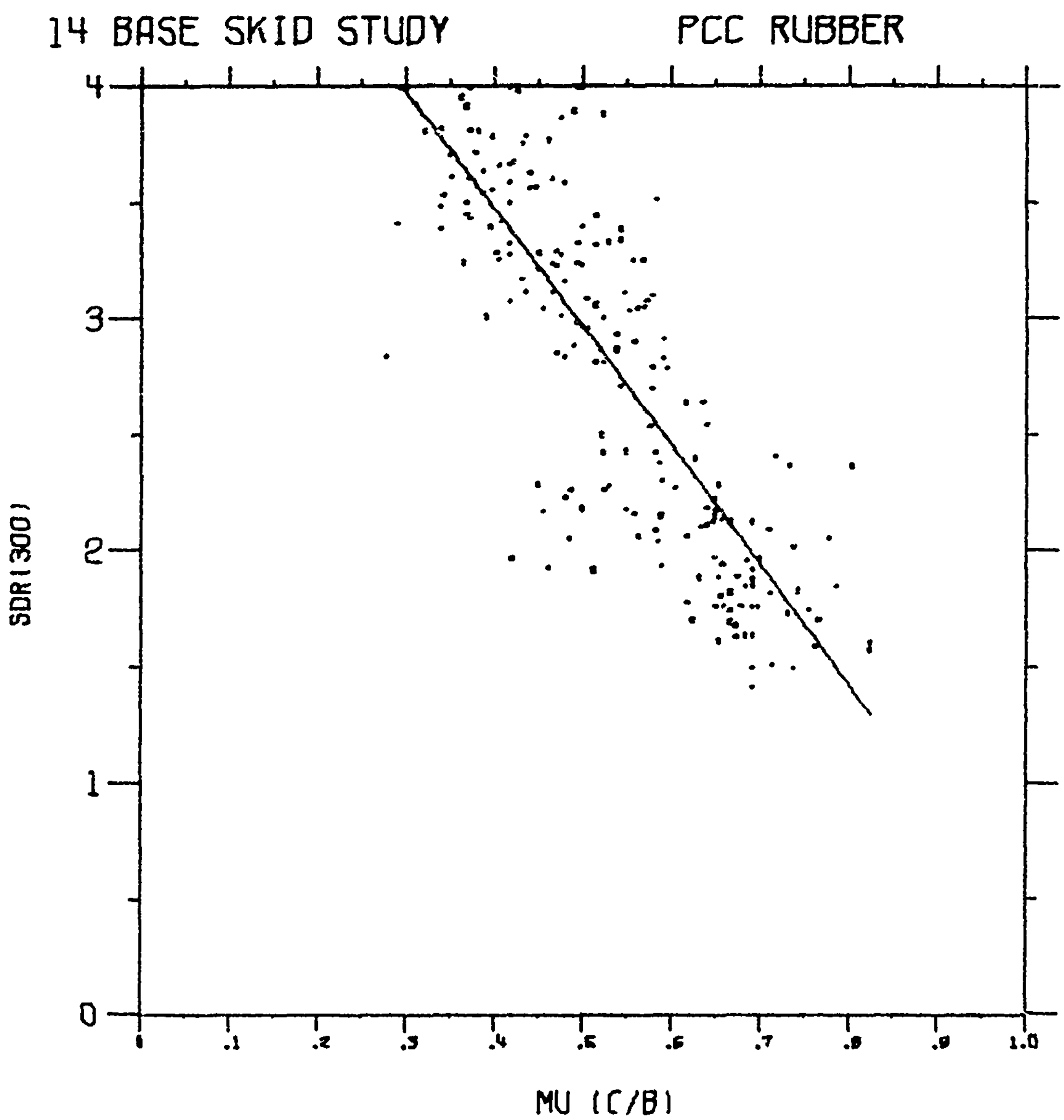


Figure 21. Mu-Meter Versus DBV Data on PCC Rubber Areas (Second Order Curve Fit).

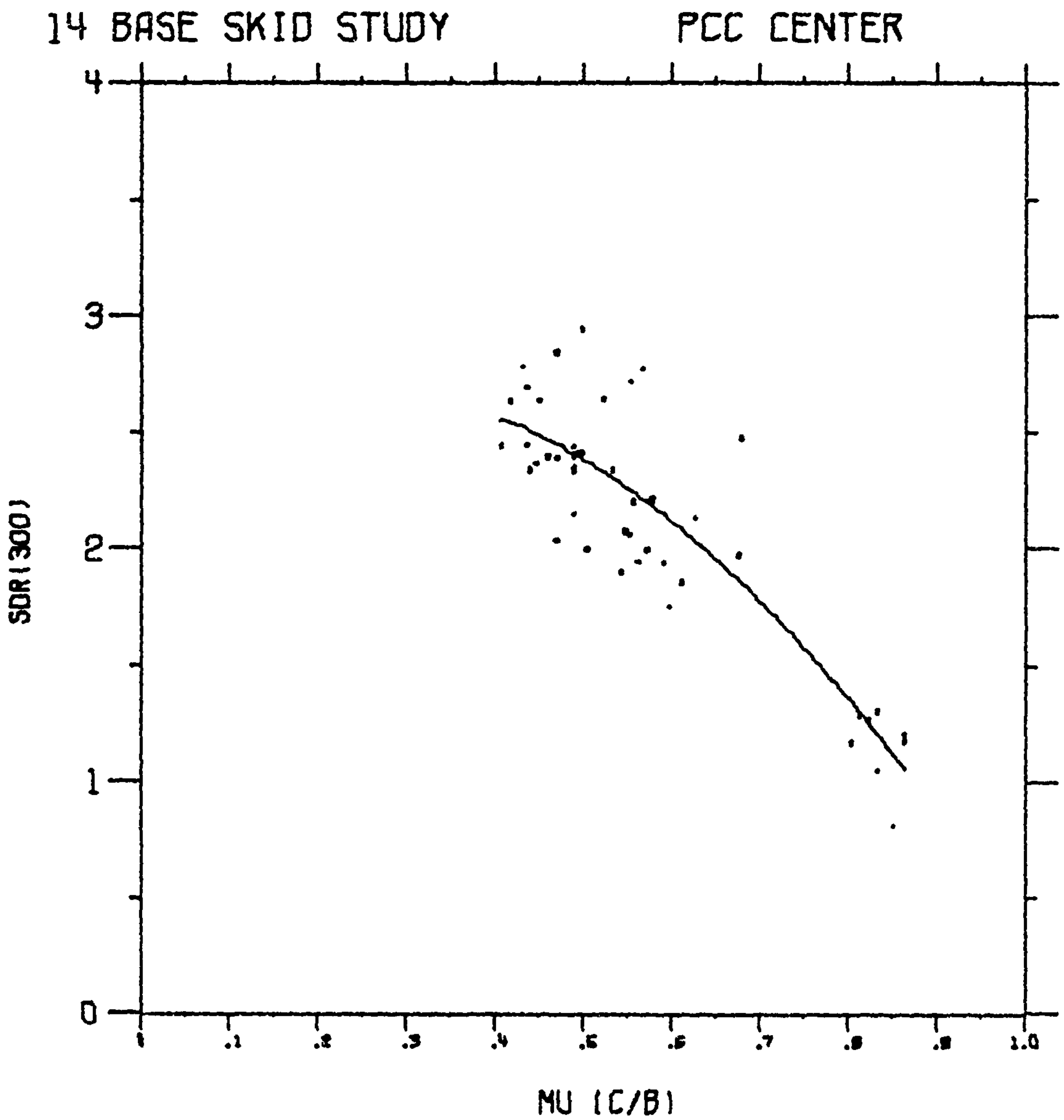


Figure 22. Mu-Meter Versus DBV Data on PCC Center Sections (Second Order Curve Fit).

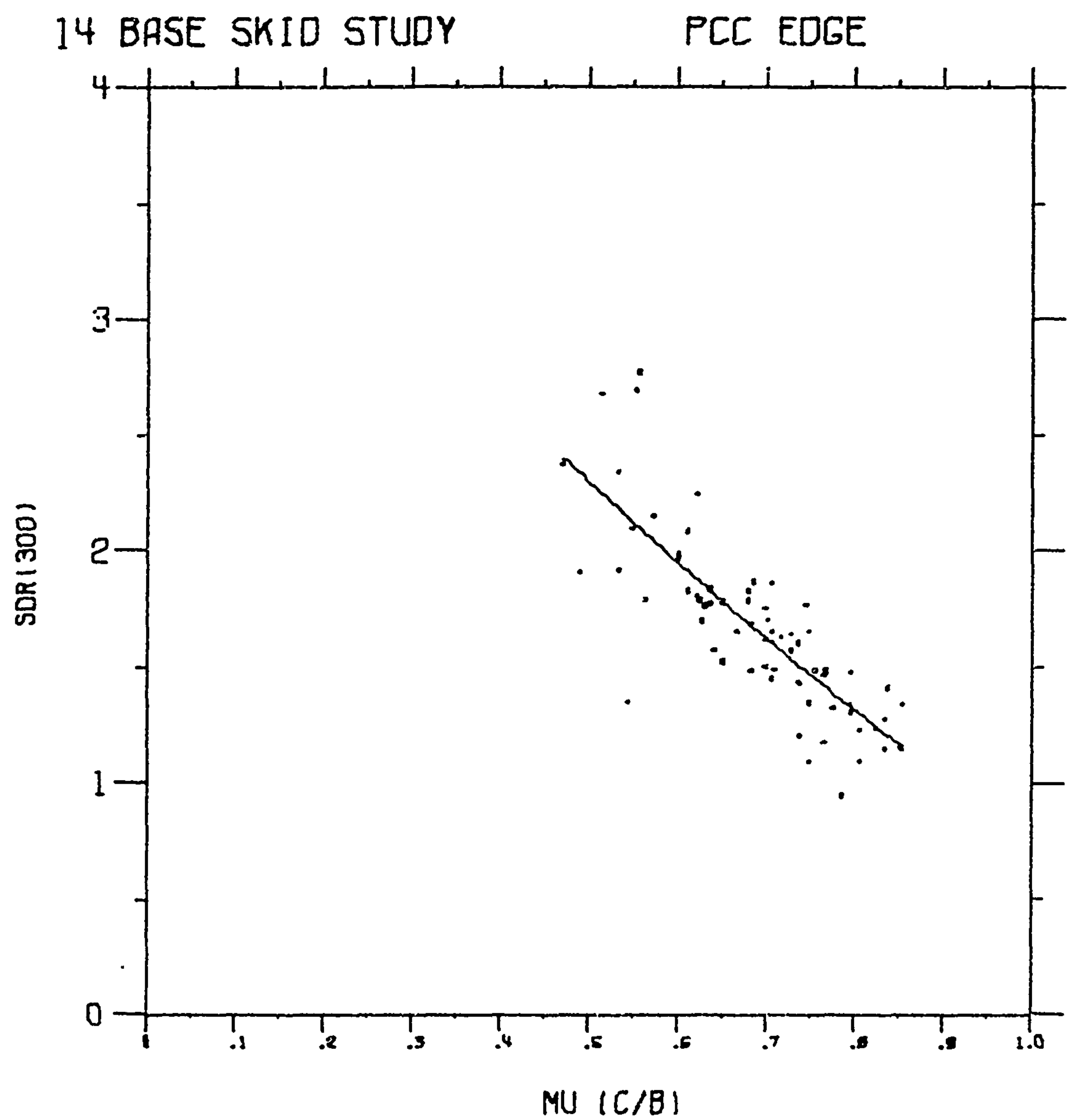


Figure 23. Mu-Meter Versus DBV Data on PCC Edge Sections (Second Order Curve Fit).

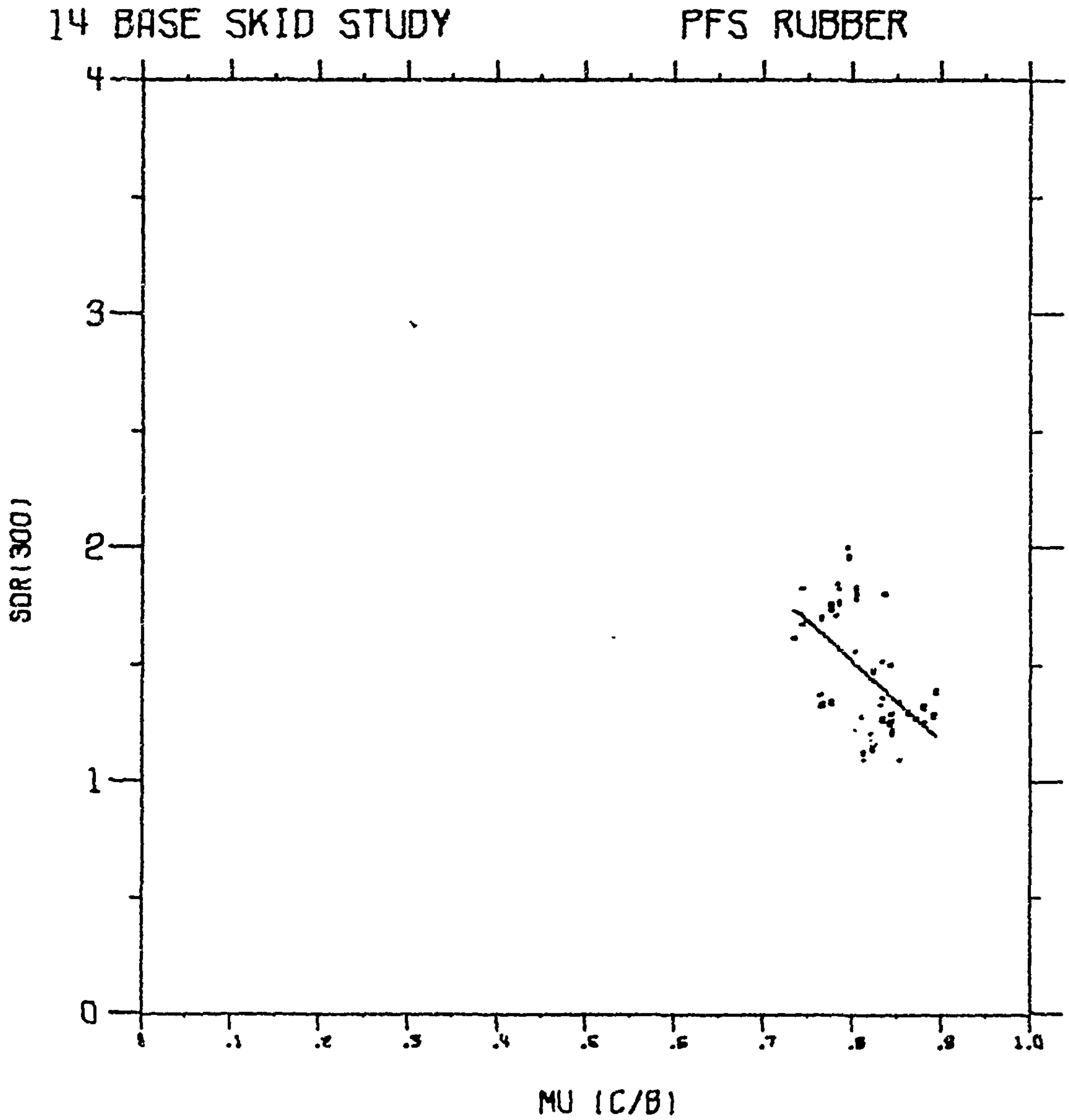


Figure 24. Mu-Meter Versus DBV Data on PFS Rubber Sections (Linear Regression Curve).

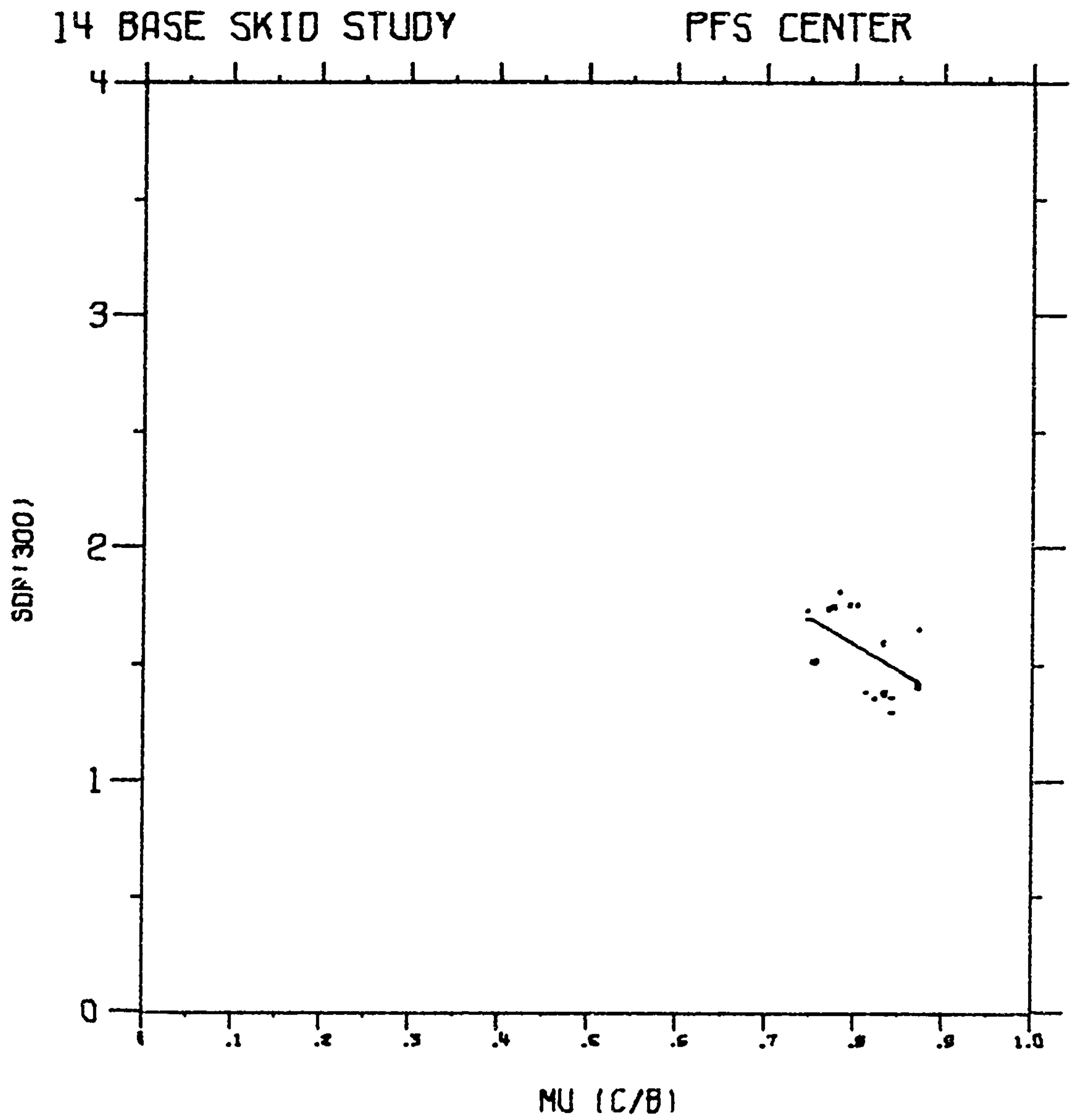


Figure 25. Mu-Meter Versus DBV Data on PFS Central Sections (Linear Regression Curve).

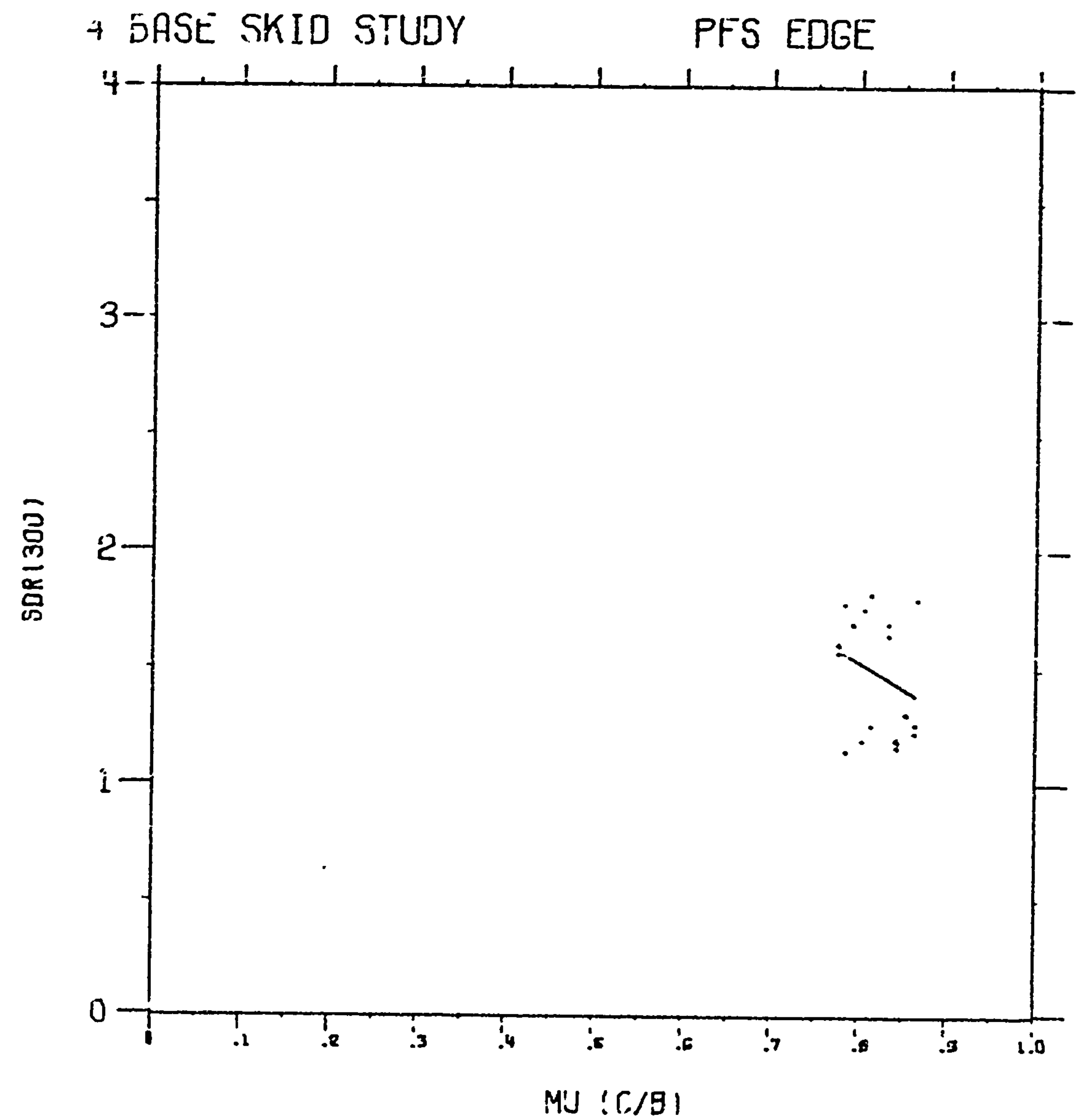


Figure 26. Mu-Meter Versus DBV Data on PFS Edge Sections (Linear Regression Curve).

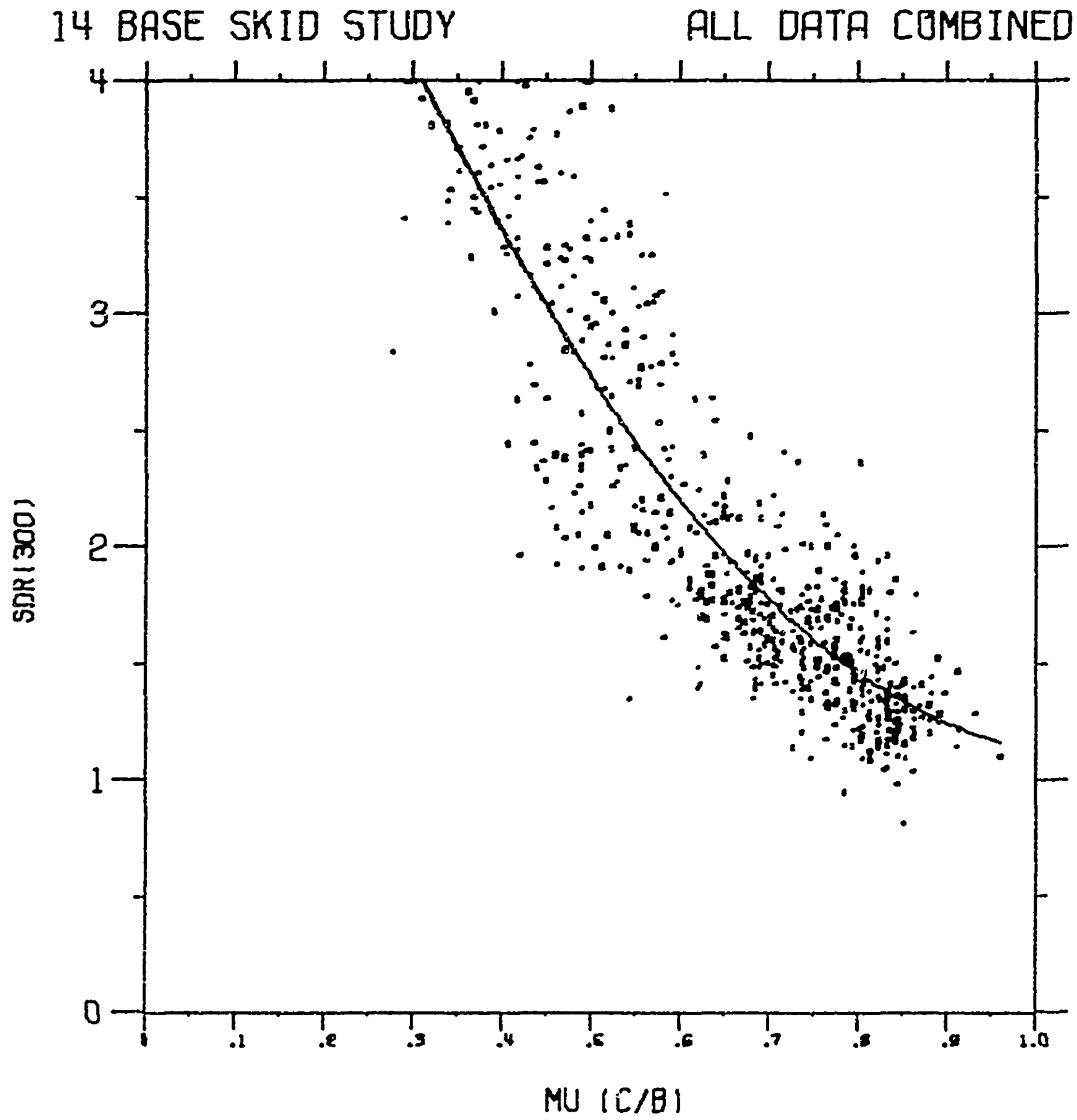


Figure 27. Mu-Meter Versus DBV Data on all Pavement Surfaces Combined (Second Order Curve Fit).

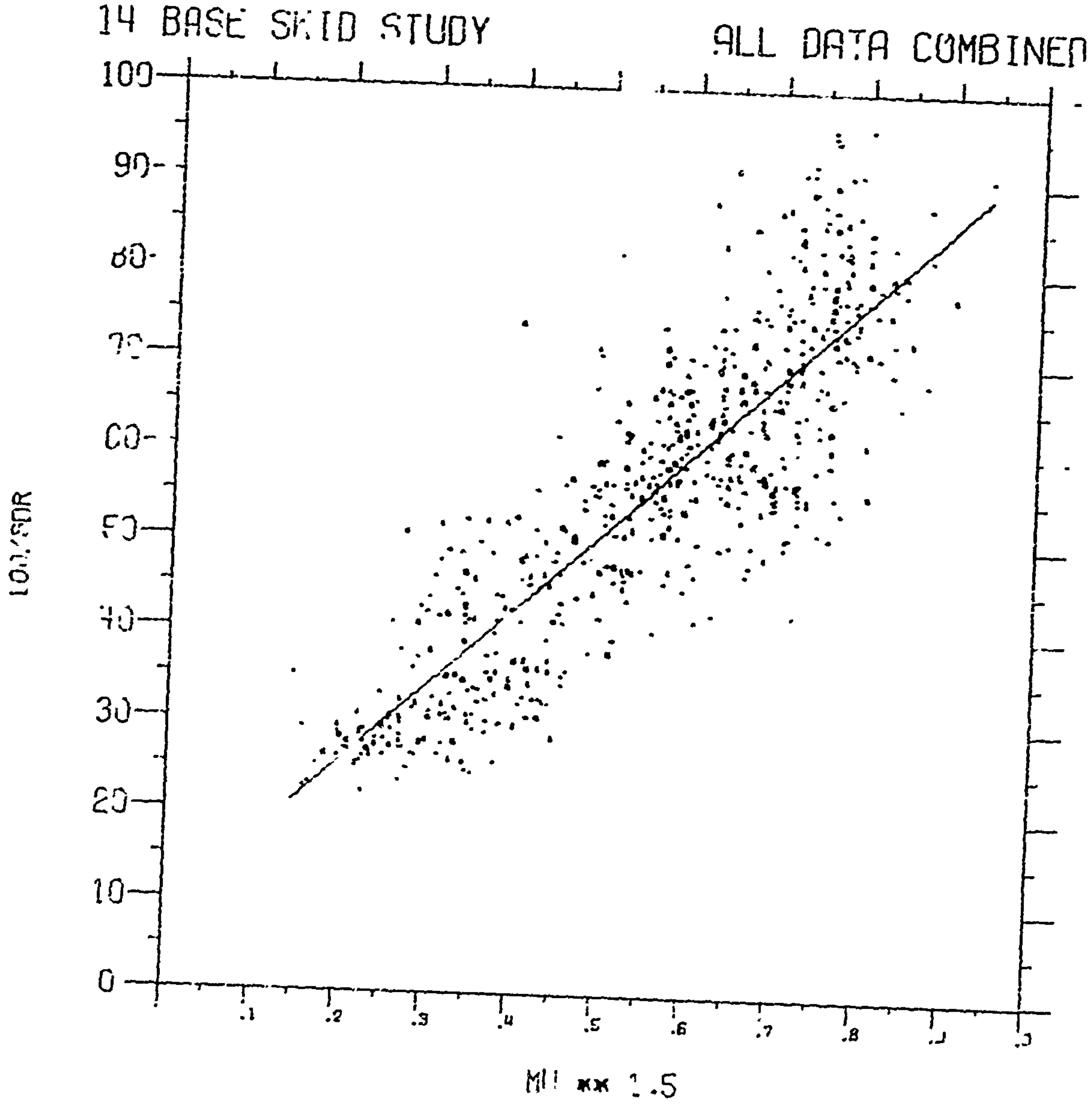


Figure 28. Mu-Meter Versus DBV Data After Adjustment of Data to Match a British Study.

Thus, while it was not possible to duplicate the British results precisely, the equation derived was similar in form and the constants determined by the computer regression were of the same magnitude as those in the British equation. Unfortunately this manipulation of the data did not result in attainment of a "better-fit" curve or in raising the simple correlation coefficient over that shown in the previous study. The simple correlation coefficient between the data shown in figure 28 over 0.8558, which was slightly less than that shown for a simple linear regression done directly on the data points. It would thus appear that no additional accuracy could be expected by using elaborate techniques to adjust data points prior to performing regression operations.

4. CONCLUSIONS ON MU-METER/DBV CORRELATION

There is a significant correlation between data gathered with the Mu-Meter and data gathered using the Diagonally Braked Vehicle. Because of the somewhat large band of variation, however, it is not feasible to use mathematical equations to compute coefficients of friction from stopping distance ratios, and vice versa.

The AFWL rating system for airfield pavements (based on a Mu-Meter value of 0.50 corresponding to a stopping distance ratio of 2.00) appears conservative as far as the Diagonally Braked Vehicle data are concerned. Based on the somewhat limited study done here, however, a change in the rating system is not recommended at this time.

5. THE EFFECT OF DIRECTION OF RUN ON MEASURED FRICTION VALUES

Early in the data-gathering phase of AFWL's research effort on skid-resistance, it was apparent that data gathered with both the Mu-Meter and the Diagonally Braked Vehicle were sensitive to the direction in which the test vehicle was traveling on the test section. Or said another way, there was an apparent difference in skid-resistance properties of the pavement measured in opposite directions.

Logic suggested that there should be some difference, of course, based on the following facts:

1. Many airfield pavements are probably "polished" much more in one direction than another, due to a preponderance of traffic in one direction.

2. The Diagonally Braked Vehicle could logically be expected to be sensitive to the wind component parallel to the direction of the test section. In one instance this wind component would serve to increase the stopping distance; in the

opposite direction, it could be expected to decrease the stopping distance.

3. The Diagonally Braked Vehicle could likewise be expected to be sensitive to any longitudinal slope along the test section. An elementry law of physics requires that any vehicle takes a longer distance to stop on a downward slope than it does on a level surface. Conversely, a vehicle stops in a shorter distance on an upward slope.

To verify if indeed there is a significant difference between skid resistance properties of airfield pavements measured in opposite directions, an analysis was made of data gathered on 6 test sections at Kincheloe AFB, Michigan. In order to make such an analysis, it was necessary to take some liberties with accepted statistical techniques. Because all the skid resistance data gathered in the standard AFWL skid resistance test are time-dependent (i.e., vary in value according to the specific time after application of water), it was not possible to compare individual data values directly. To remove the time-dependent nature of the data points, regression curves were passed through the data points gathered while the test vehicles traveled in one direction only; a similar curve was then passed through the data points gathered while the test vehicles traveled in the opposite direction. A comparison was then made of individual points along the two regression curves in one minute intervals between three minutes after application of water through 30 minutes after application of water. The mean of the difference between points along these curves was then computed. A measure of the experimental error was found by estimating the standard deviation of the individual points from the regression line of which they were a part. This was done by using the range of deviations from smallest to largest, as suggested on page 39 of ref. 28. This information was desired in order to make a standard statistical test to determine if there were a significant difference between the paired points along the 2 curves. If there were a significant difference, then it could be said rather conclusively that the 2 devices used in the AFWL standard skid-resistance test are capable of detecting directional differences in skid-resistance properties. Table 9 is a compilation of the test results on data gathered with the Mu-Meter. Figures 29 through 34 are the regression curves from which table 9 was derived.

The obvious conclusion to draw after examination of the data in table 9 is that the Mu-Meter apparently does detect directional differences in skid-resistance properties. The fact that the nontraffic edge section, Test Section AA, did not have significantly different directional skid resistance properties serves to support an earlier contention that traffic has a directional polishing effect.

A similar analysis was made of the Diagonally Braked Vehicle data gathered at Kincheloe AFB, and the results are shown in table 10. Figures 35 through 40 are the regression curves from which the data were derived. Similar conclusions can be drawn from examination of table 10 - the Diagonally Braked Vehicle apparently detects directional differences in skid resistance properties.

Based on the evidence presented, it appears that some airfield pavements exhibit slightly different skid resistance properties in opposing directions. Since the results in the AFWL standard skid resistance test are based on regression curves passed through all data points gathered, this slight difference is masked and tends to disappear. Based on the fact that the difference (through apparently statistically significant) is very small, there is no valid reason to take it into account when a pavement surface is evaluated. The "average" value obtained from a regression curve through all points appears to be the most useful skid resistance indicator.

Table 9

RESULTS OF SIGNIFICANCE TESTS ON MU-METER DATA, KINCHELOE AFB

Section	Mean Difference Between Points Along 2 Regression Curves	Standard Deviation	Value of t	Significant @ 1% Level	Significant @ 5% Level
C	0.0496	0.0163	9.62	Yes	Yes
D	0.0159	0.0097	5.18	Yes	Yes
E	0.0155	0.0130	3.77	Yes	Yes
F	0.0426	0.0085	15.84	Yes	Yes
G	0.1159	0.0293	12.50	Yes	Yes
AA	0.0086	0.0163	1.67	No	No

Table 10

RESULTS OF SIGNIFICANCE TESTS ON DIAGONALLY BRAKED VEHICLE DATA, KINCHELOE AFB

C	0.0685	0.0702	2.76	No	Yes
D	0.1234	0.0421	8.29	Yes	Yes
E	0.1916	0.0211	25.68	Yes	Yes
F	0.6695	0.0562	33.69	Yes	Yes
G	0.3585	0.1123	9.03	Yes	Yes
AA	0.2357	0.0316	21.10	Yes	Yes

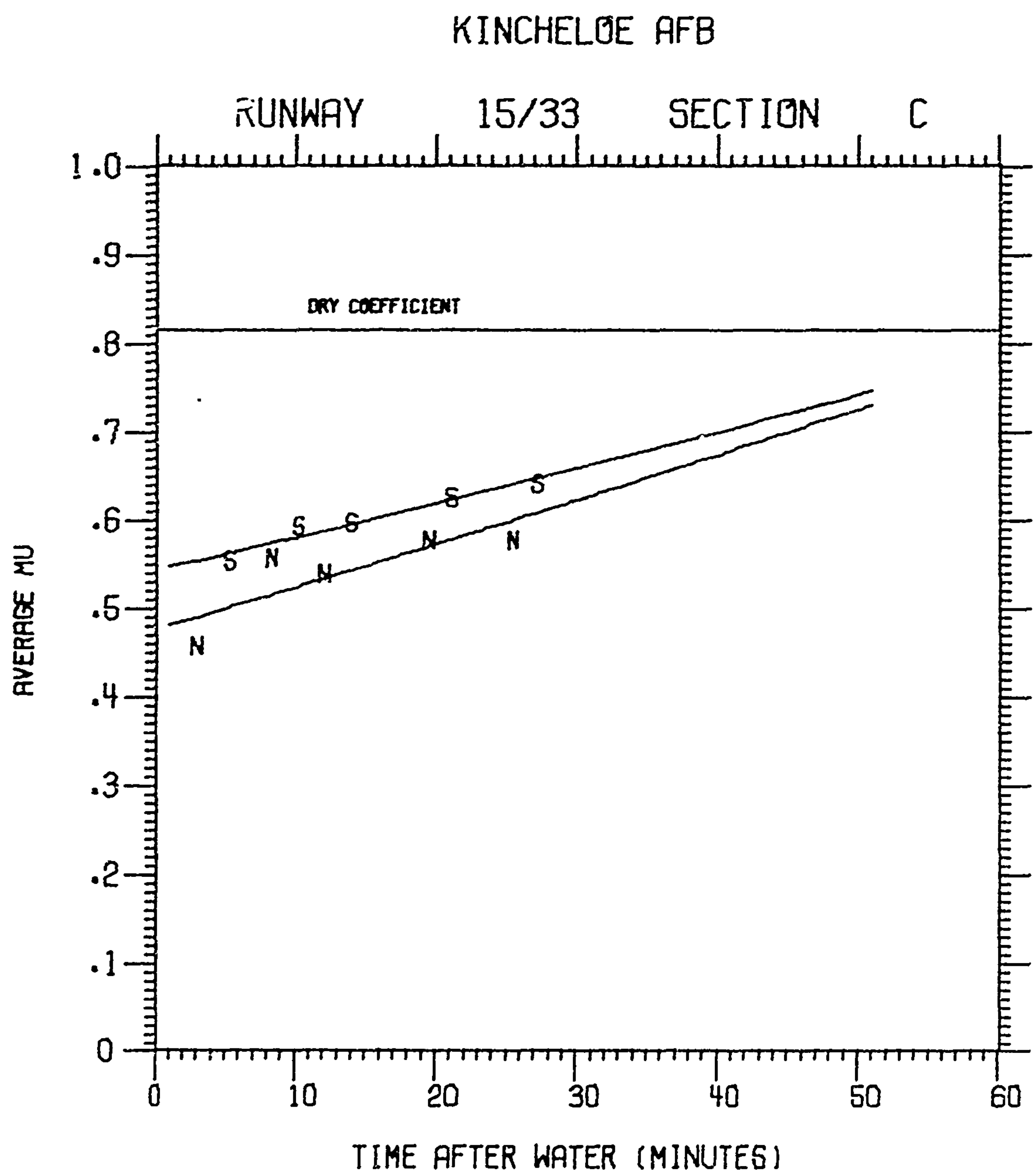


Figure 29. Regression Curves Through Uni-Directional Mu-Meter Points, Test Section C, Kincheloe AFB.

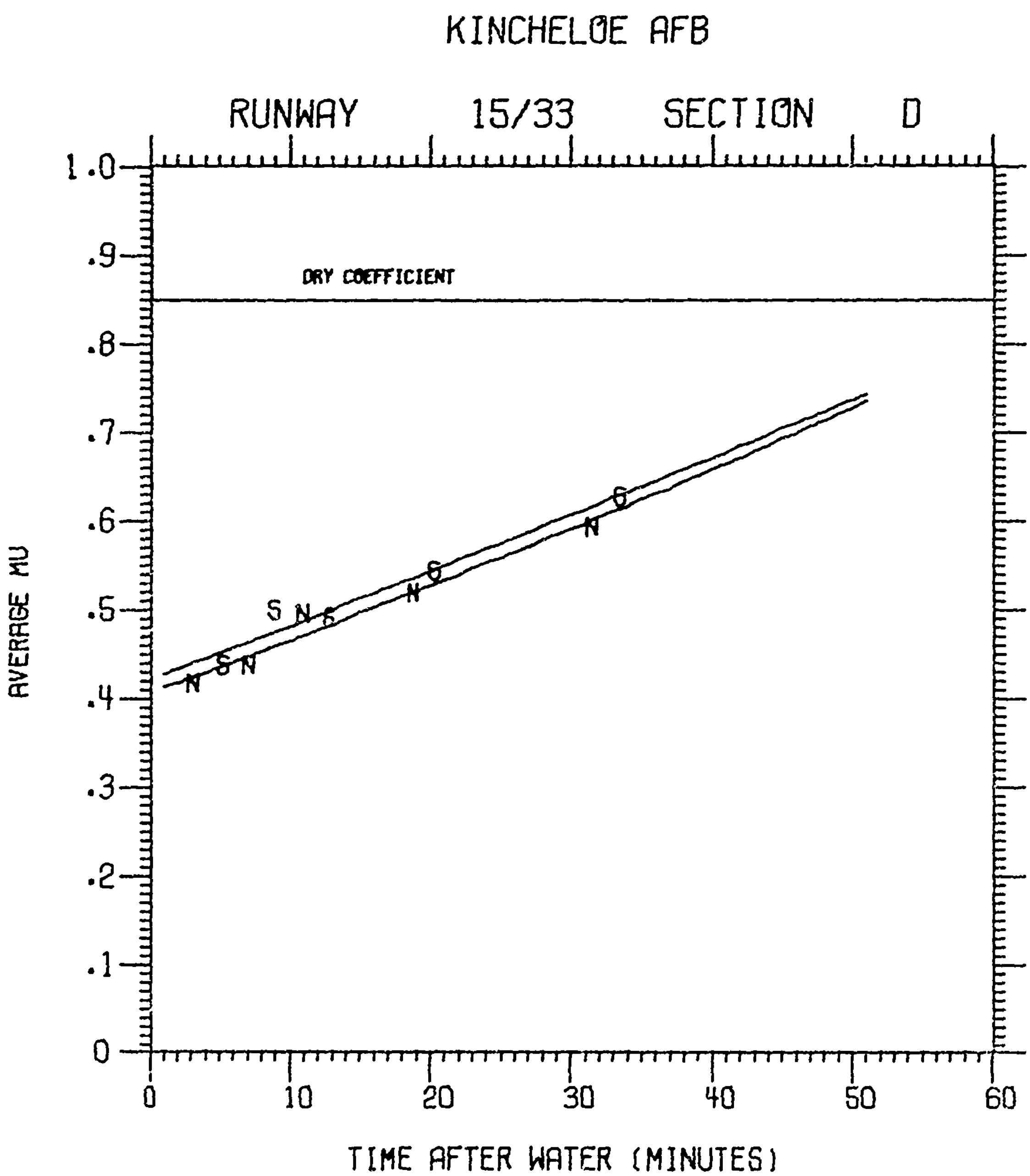


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Figure 30. Regression Curves Through Uni-Directional Mu-Meter Points, Test Section D, Kincheloe AFB.

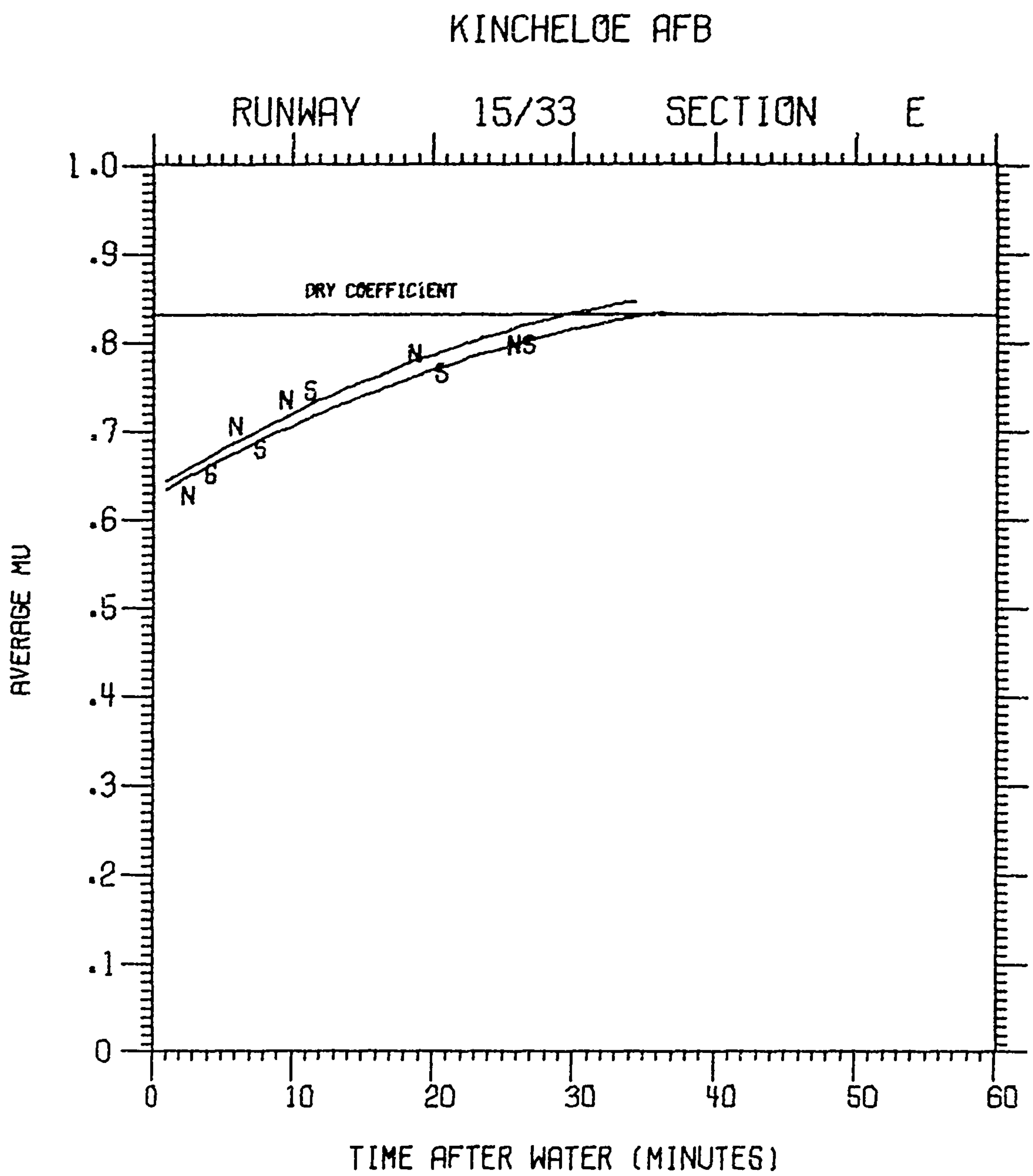

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Figure 31. Regression Curves Through Uni-Directional Mu-Meter Points, Test Section E, Kincheloe AFB.

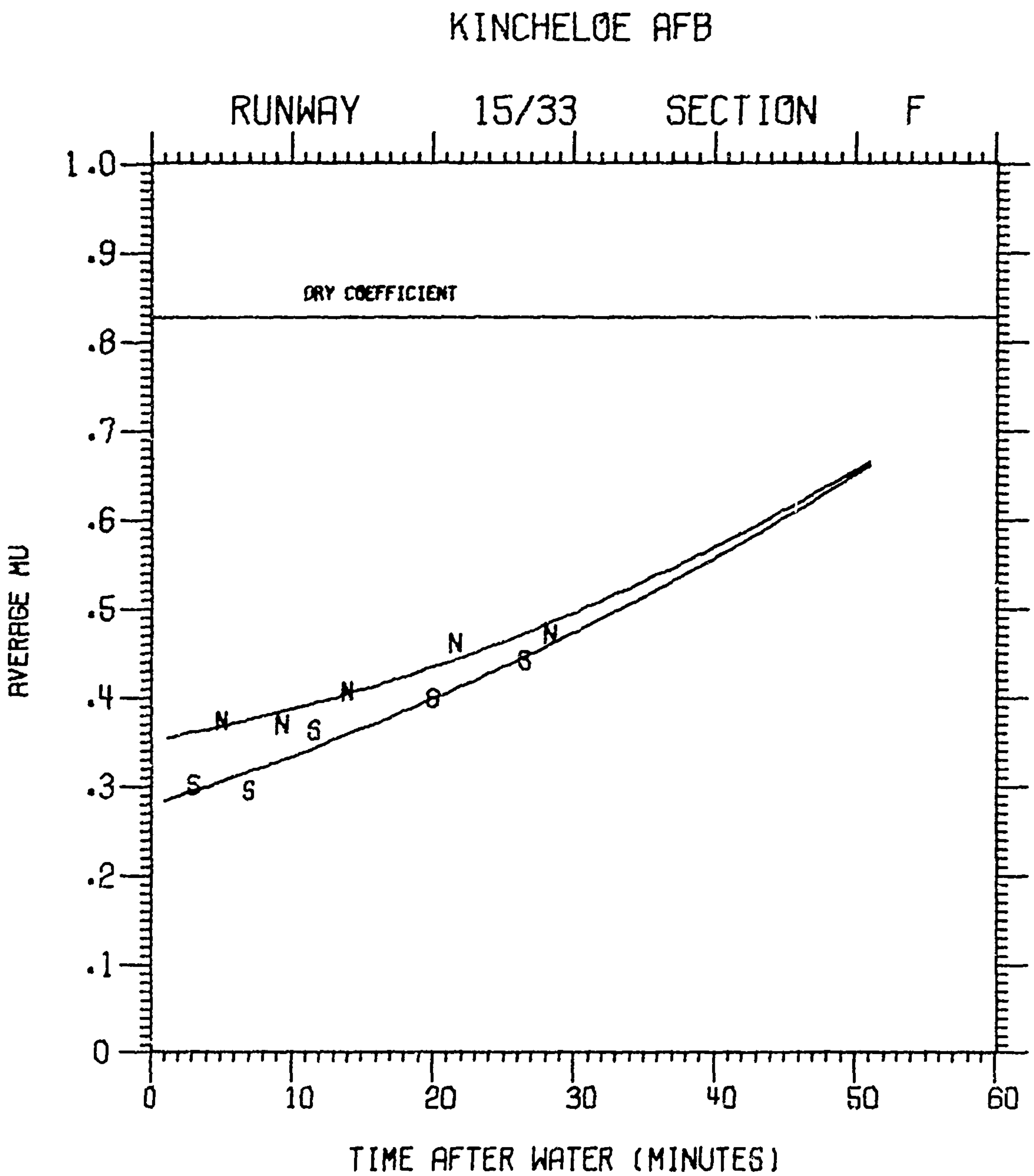

Figure 32. Regression Curves Through Uni-Directional Mu-Meter Points, Test Section F, Kincheloe AFB.

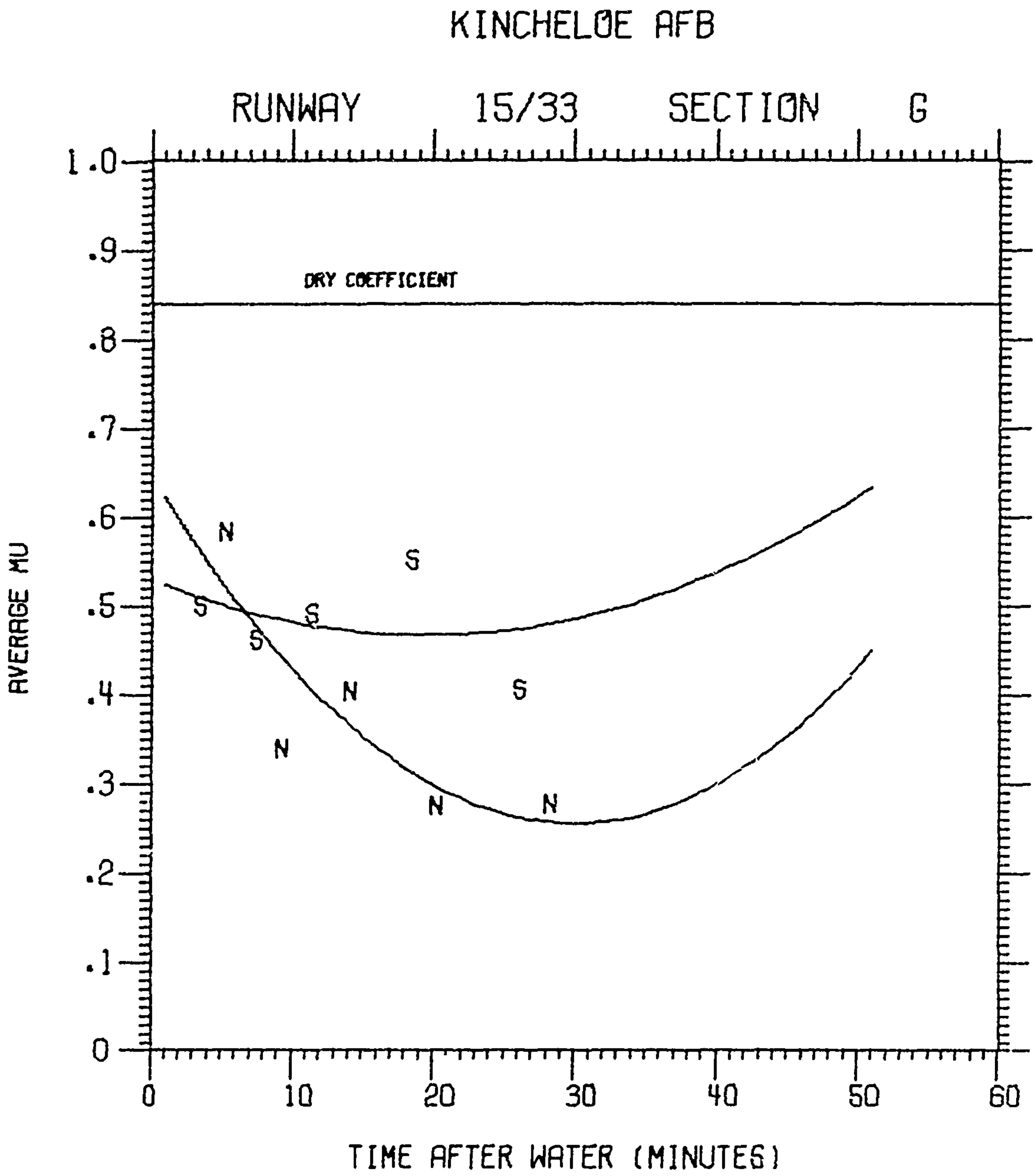

Figure 33. Regression Curves Through Uni-Directional Mu-Meter Points, Test Section G, Kincheloe AFB.

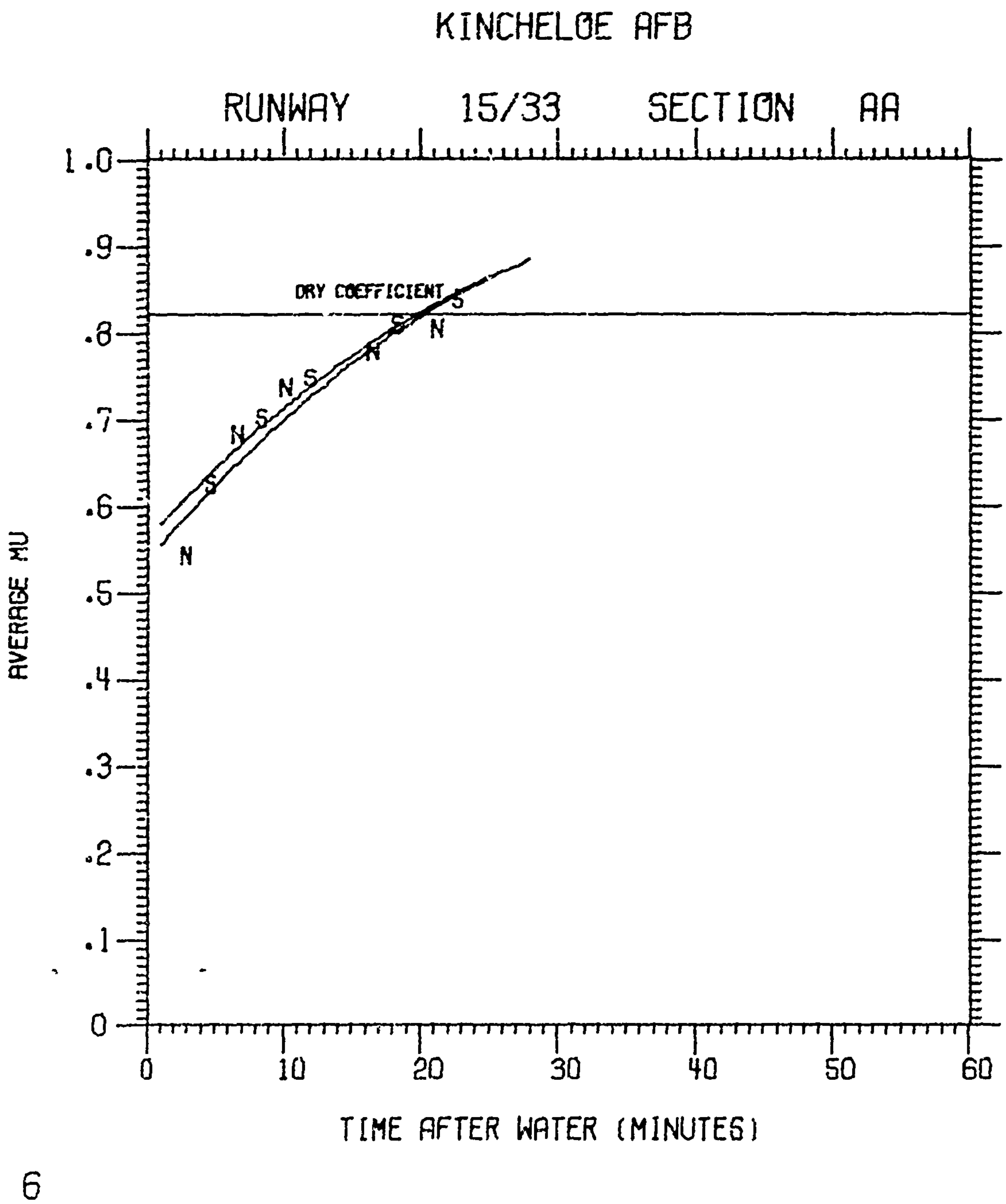

Figure 34. Regression Curves Through Uni-Directional Mu-Meter Points, Test Section AA, Kincheloe AFB.

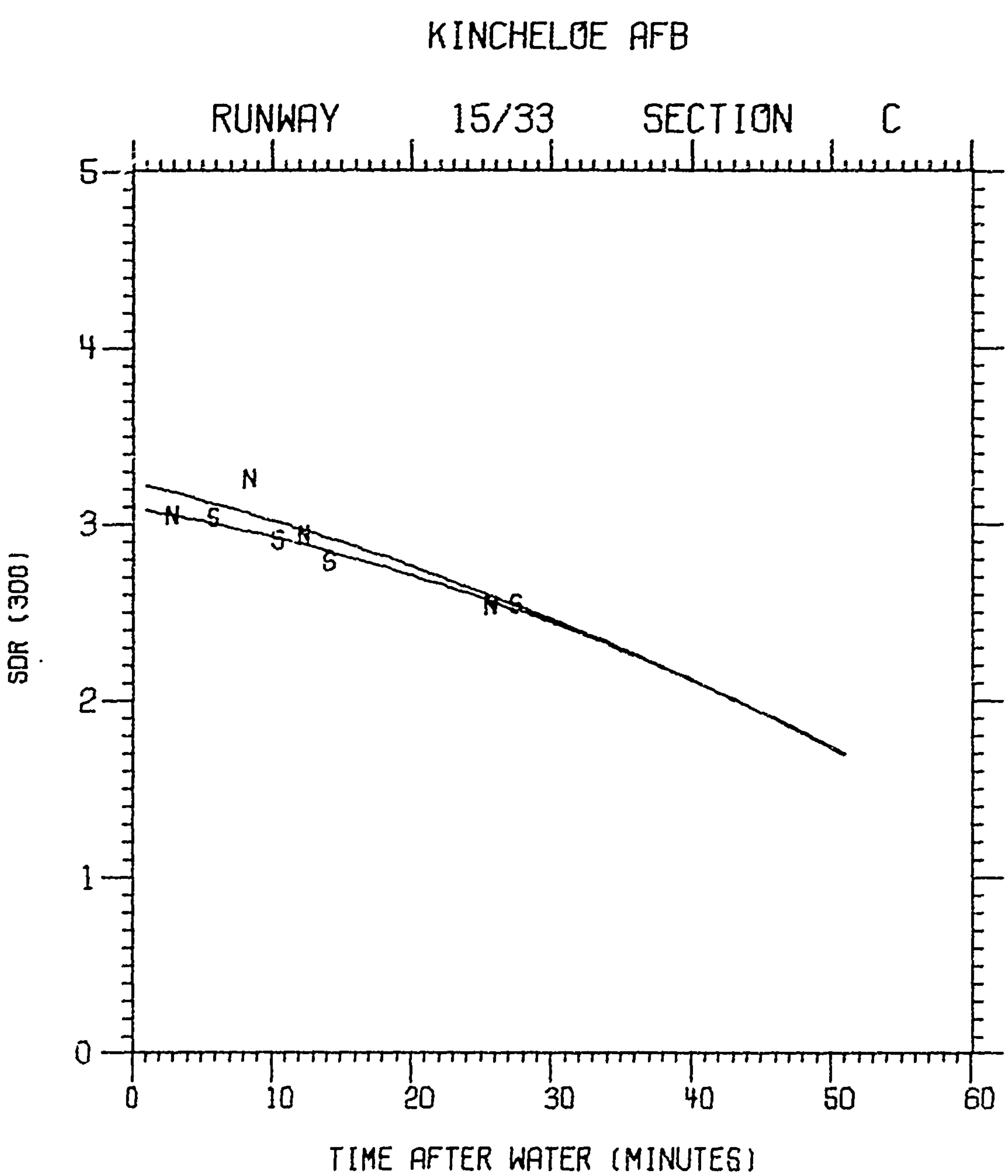

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Figure 35. Regression Curves Through Uni-Directional DBV Data, Test Section C, Kincheloe AFB.

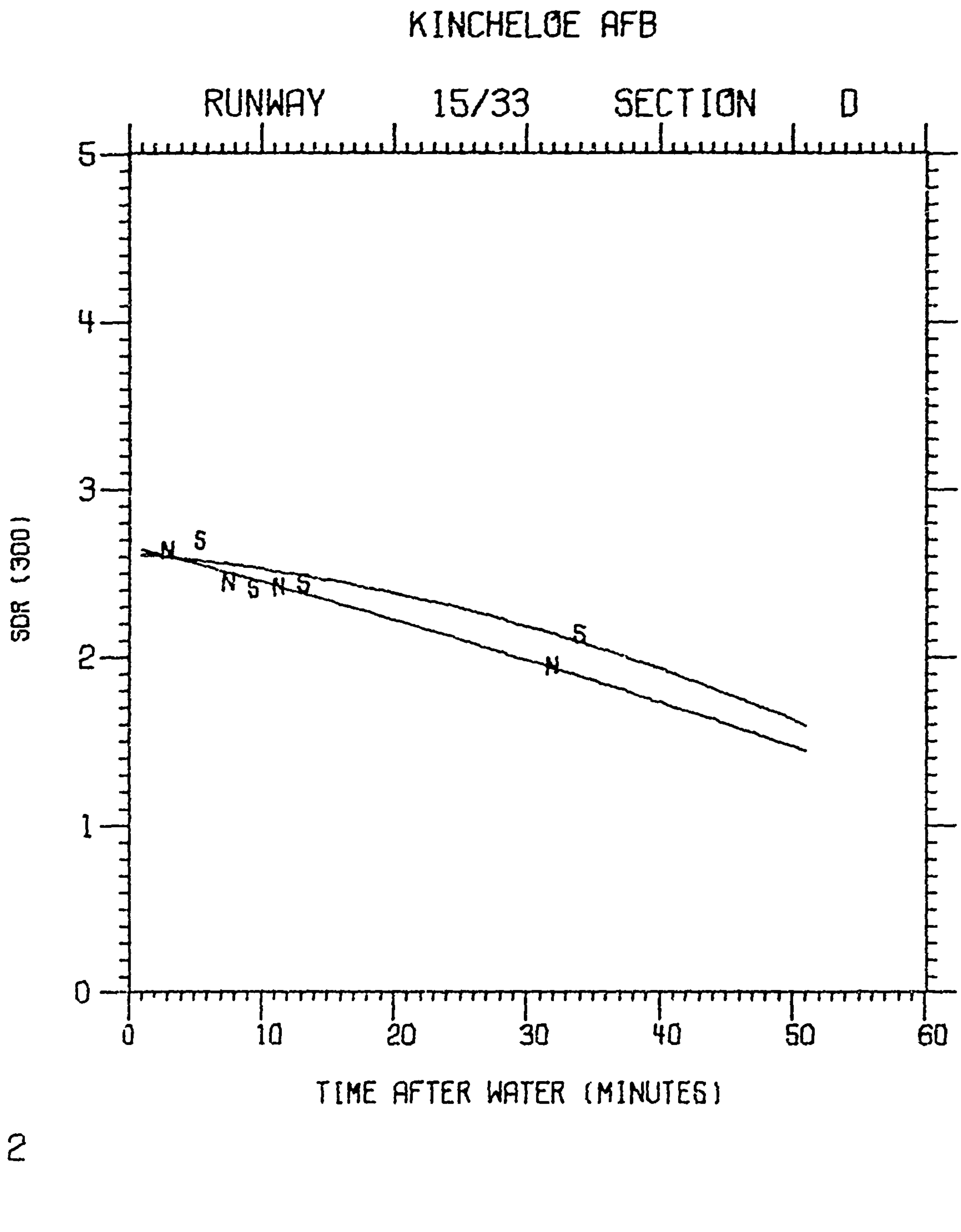

Figure 36. Regression Curves Through Uni-Directional DBV Data, Test Section D, Kincheloe AFB.

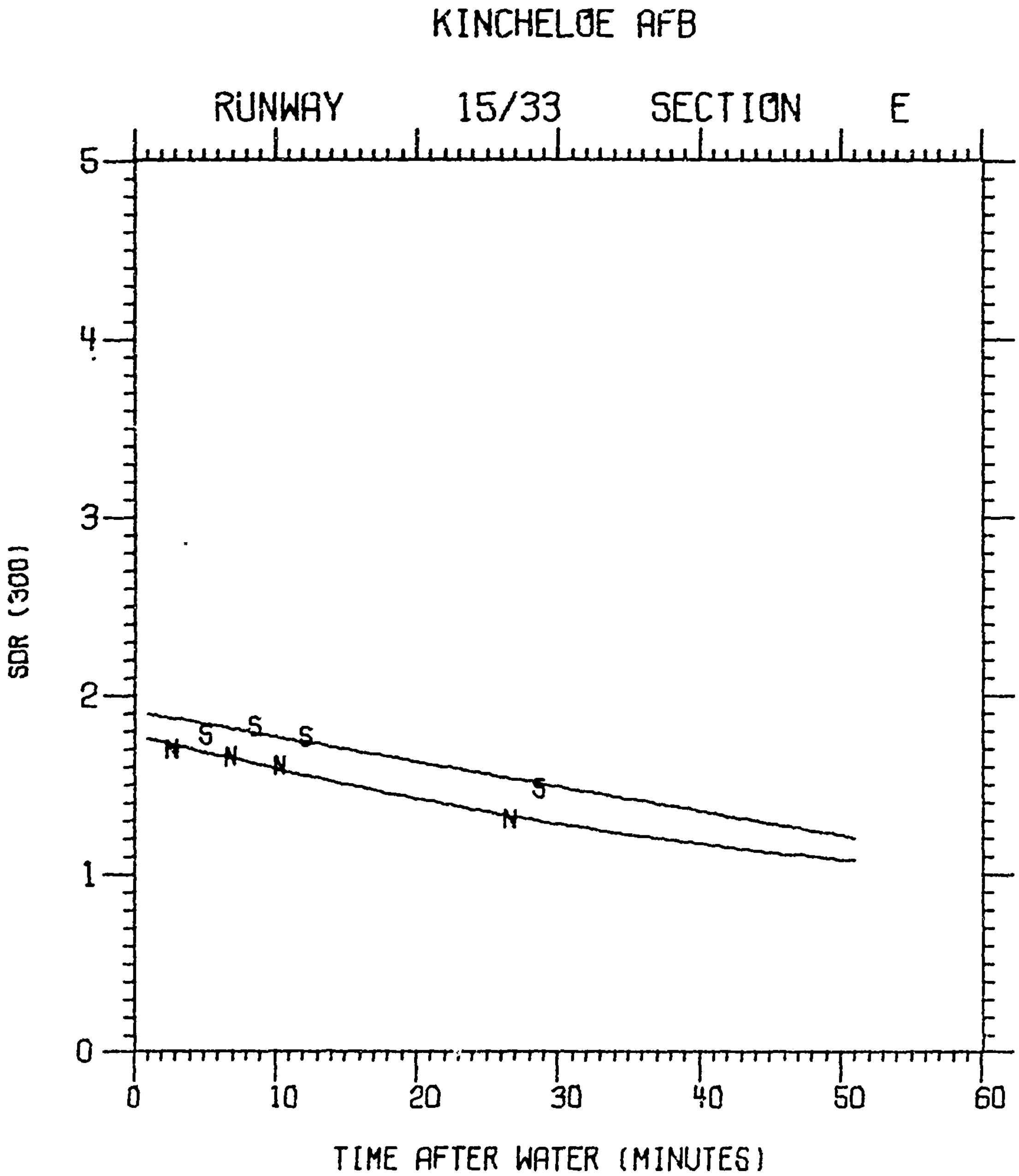

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Figure 37. Regression Curves Through Uni-Directional DBV Data, Test Section E, Kincheloe AFB.

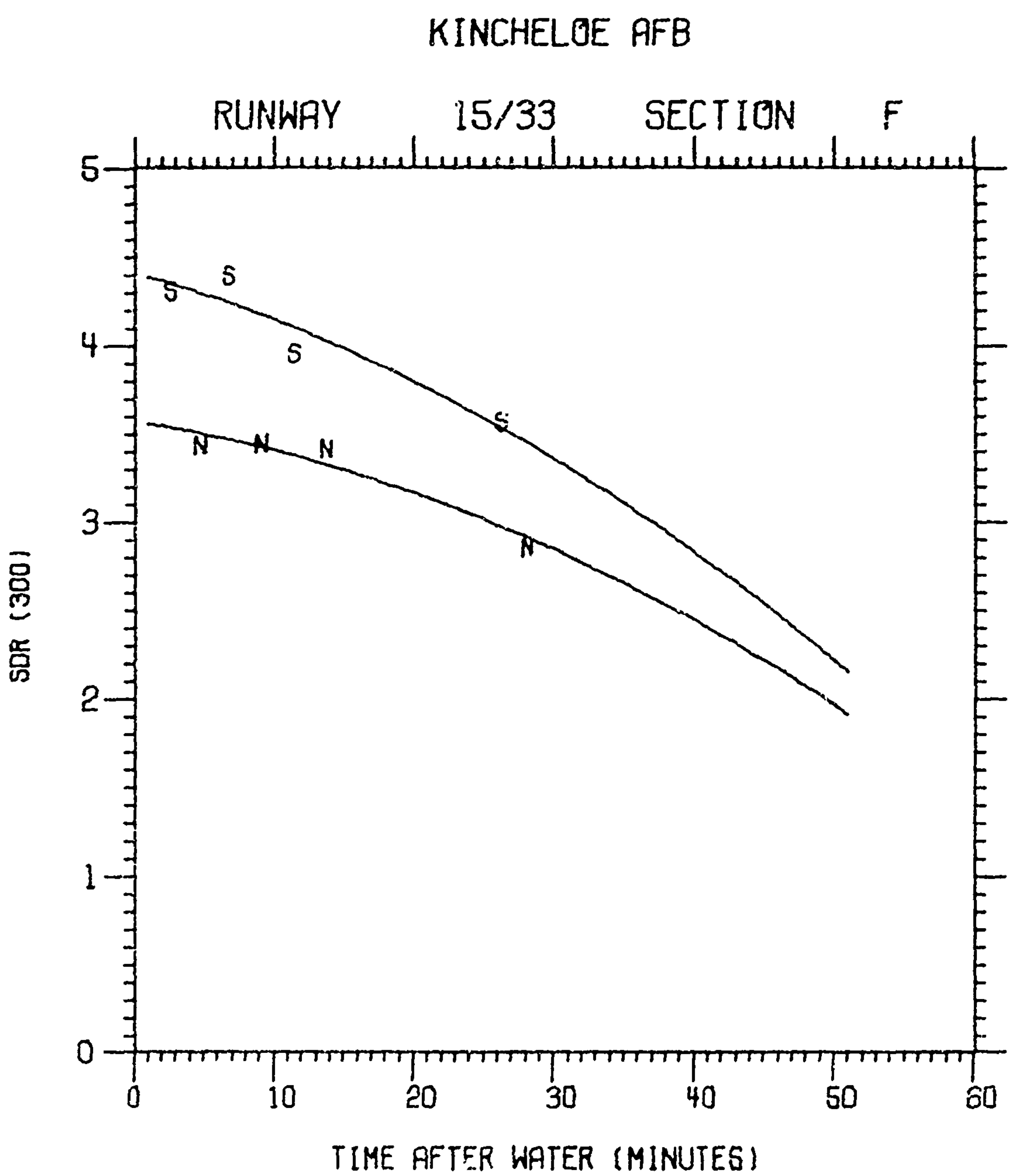

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Figure 38. Regression Curves Through Uni-Directional DBV Data, Test Section F, Kincheloe AFB.

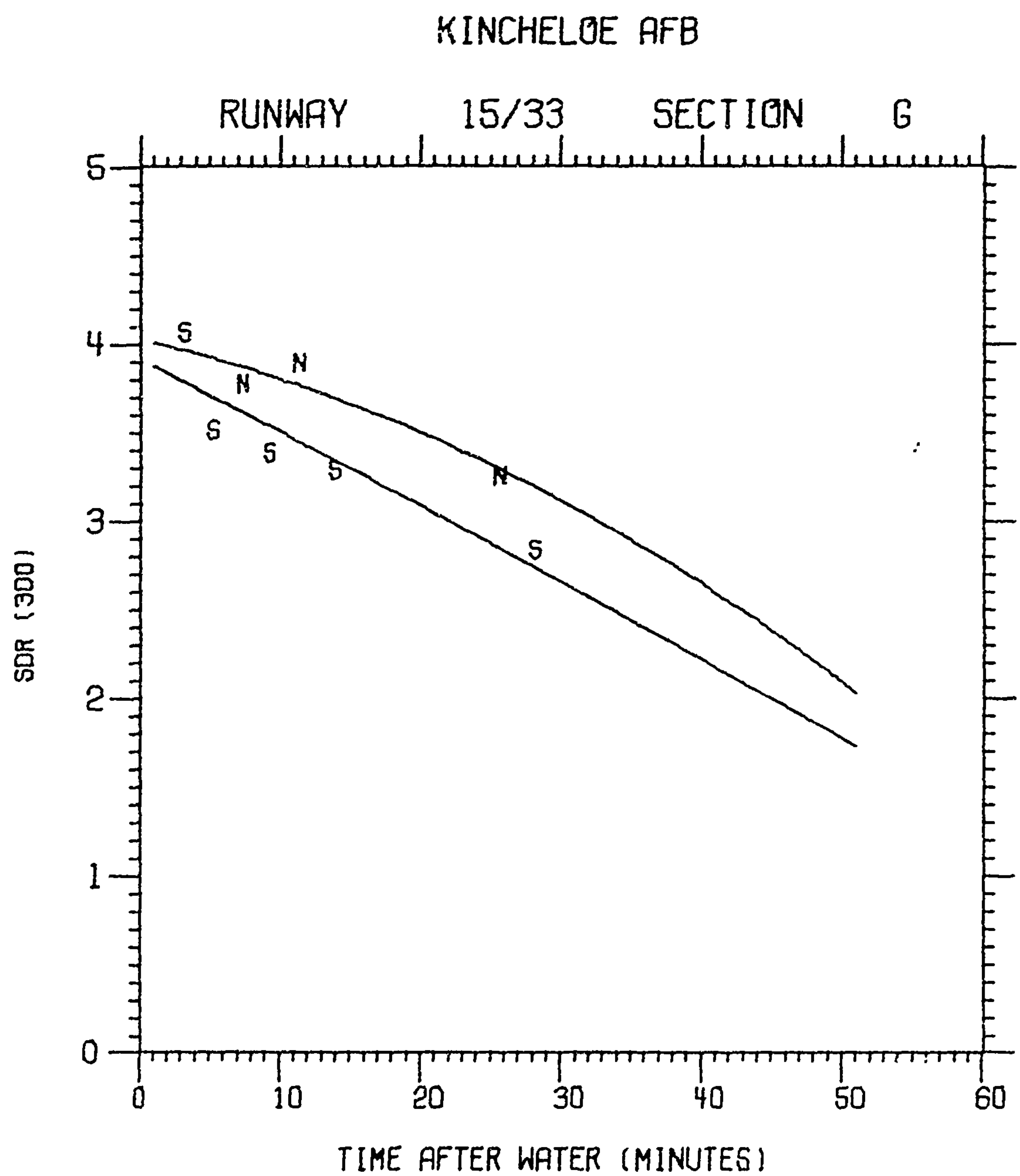

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Figure 39. Regression Curves Through Uni-Directional DBV Data, Test Section G, Kincheloe AFB.

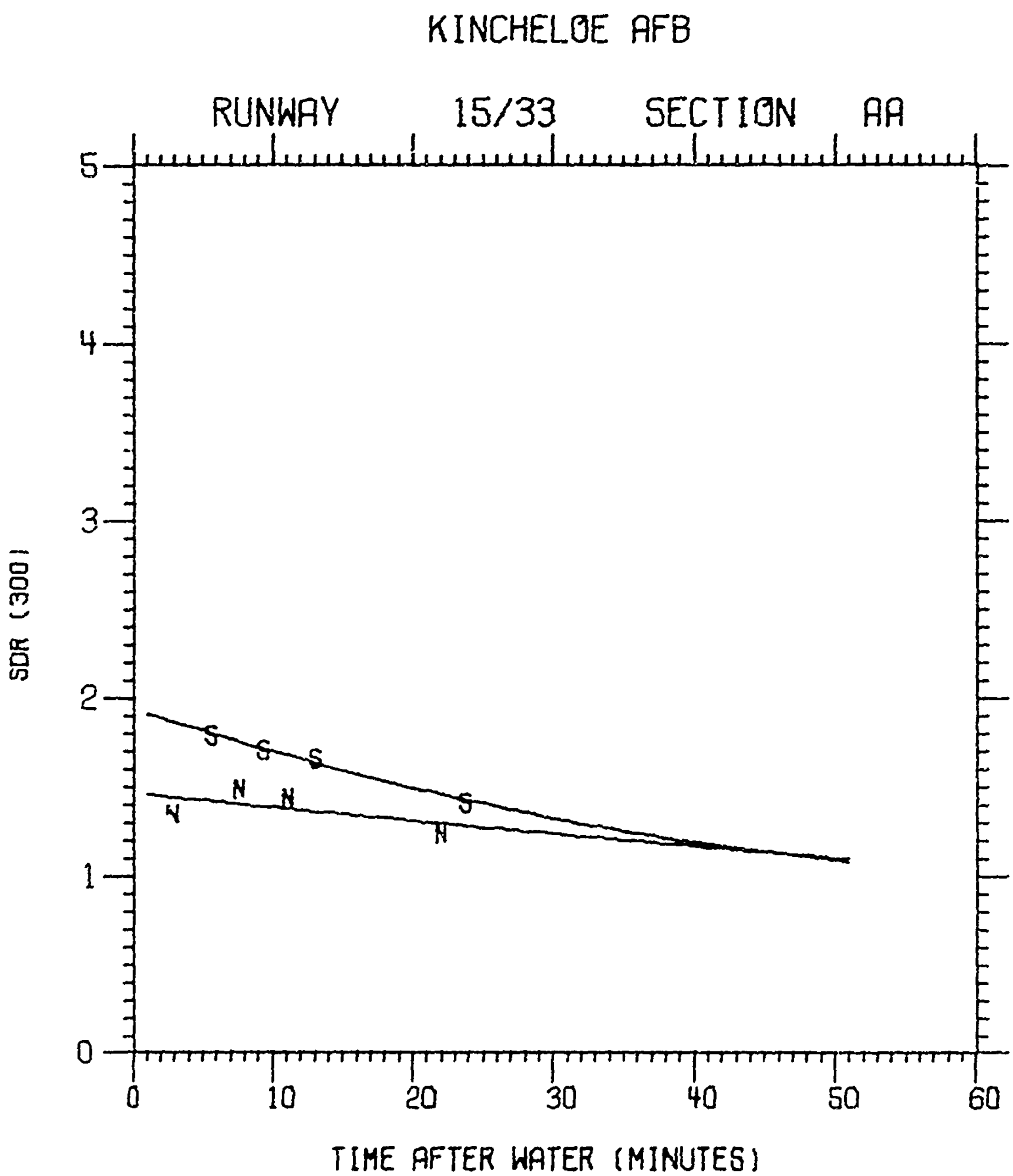

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Figure 40. Regression Curves Through Uni-Directional DBV Data, Test Section AA, Kincheloe AFB.

APPENDIX A

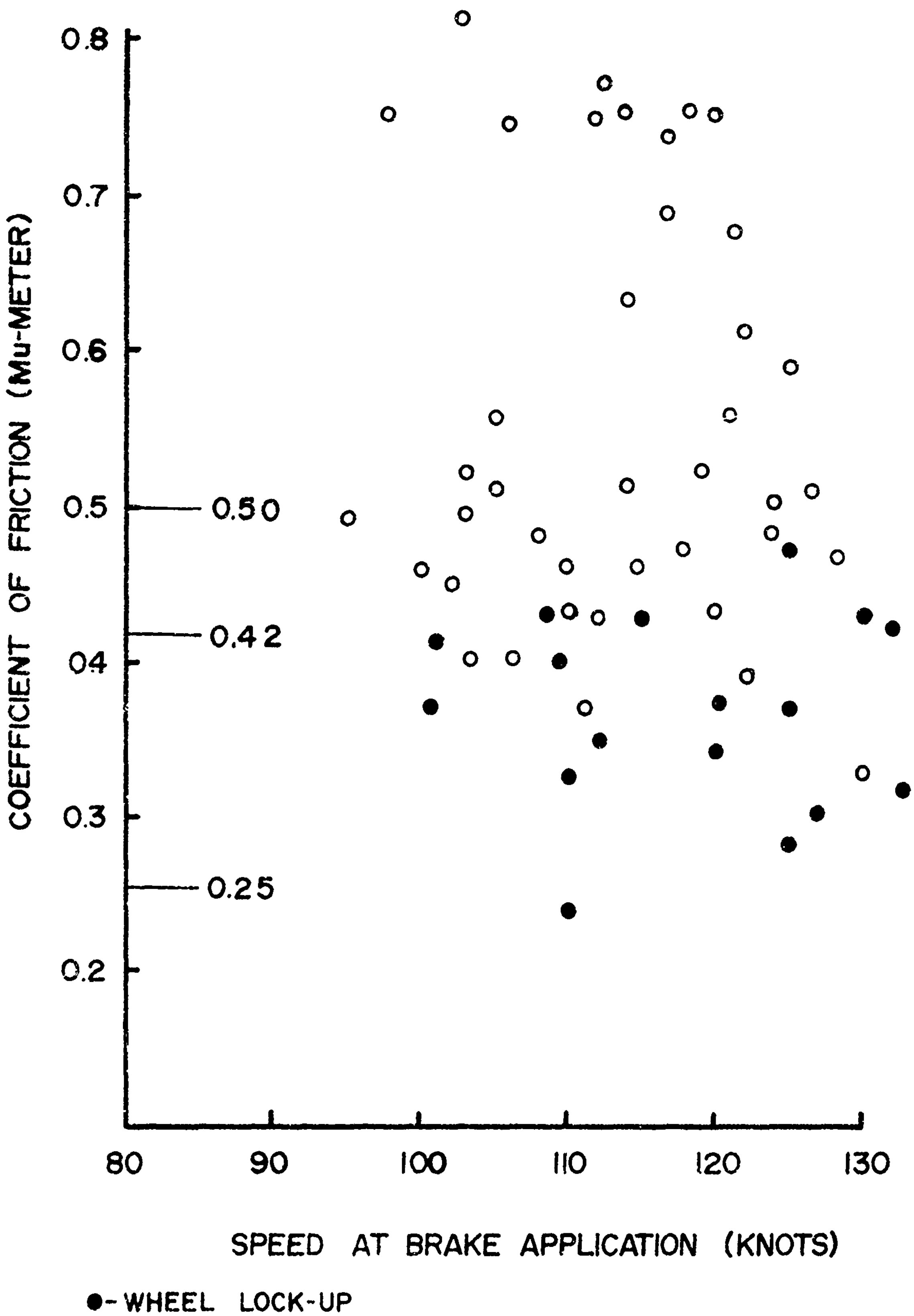
DEVELOPMENT OF THE AFWL SKID RESISTANCE RATING CHARTS

Figures 41 and 42 are plots of actual aircraft data gathered during joint tests conducted by the Federal Aviation Administration (FAA), the United States Air Force (USAF) and the National Aeronautics and Space Administration (NASA). One group of tests using a Boeing 727-100 aircraft were conducted during the period 4-16 October 1971, and data were published in a progress report by the FAA (ref 26). A second group of tests using a Douglas DC-9 were conducted during the period 12-25 February 1972, and data were published in a Langley Working Paper by NASA (ref 27). All of the data points which had complete information available from the two sets of tests were plotted in figures 41 and 42. The solid dots represent those data points where wheel lock-up occurred, indicating a high probability for hydroplaning. These two figures formed the basis for the rating charts shown in tables 1 and 2.

If horizontal lines are drawn on figure 41 at the points where the coefficient of friction equals 0.25, 0.42, and 0.50, they divide the figure into four fairly distinct zones, and these four zones formed the basis for the Mu-Meter Airfield Pavement Rating Chart. Likewise, if horizontal lines are drawn on figure 42 at the points where the DBV stopping distance ratio equals 2.0, 2.5, and 3.5, they divide this figure into four fairly distinct zones. Again, these zones correspond to the values shown in the Stopping Distance/Airfield Pavement Rating Chart.

Admittedly, any rating system devised using the methods described above must be considered somewhat arbitrary. Unfortunately, there is a lack of extensive data gathered under controlled conditions with which to further verify the rating charts developed by AFWL. Proposals are underway by the NATO Flight Safety Working Party to standardize on a somewhat different rating chart than those shown in tables 1 and 2. This proposal is reproduced as table 11. There are little data to support disagreement with this proposal, other than the fact that the Air Force had already instituted an operational testing program using the AFWL pavement rating charts at the time the proposed NATO chart was released, and the fact that the AFWL correlation study detailed in Section V shows that the DBV stopping distance ratios in table 11 are much too conservative.

It is possible that additional research will show the necessity for adjusting the AFWL pavement rating charts shown in tables 1 and 2. At the time of publication of this technical report, however, they represented the official US Air Force rating system being used by the Air Force Civil Engineering Center in their operational testing program, and probably the best system available under current technology.



Figurc 41. Data Used in Deriving the AFWL Mu-Meter Rating Chart.

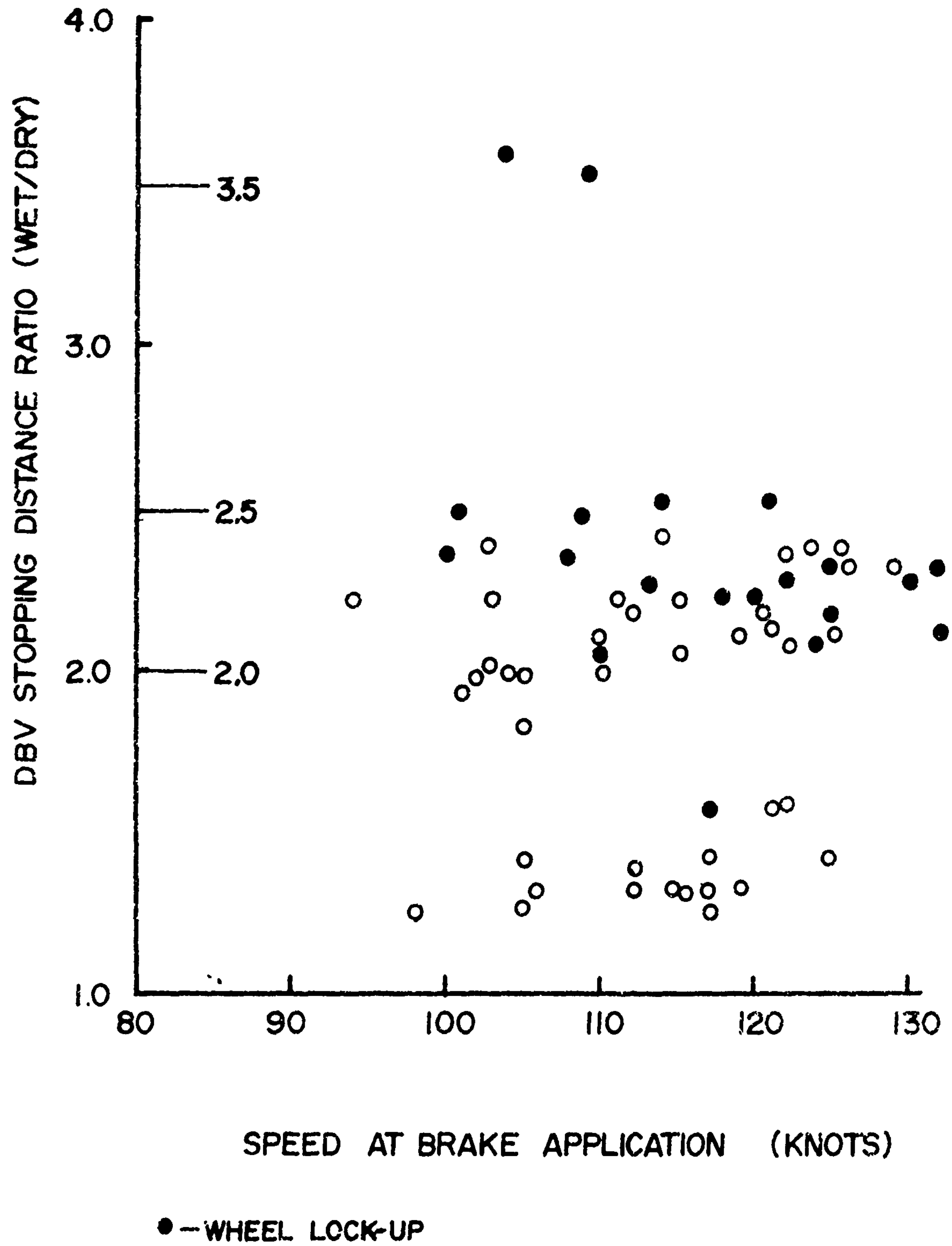


Figure 42. Data Used in Deriving the AFWL DBV-SDR Rating Chart.

Table 11

CONVERSION TABLE

Braking Code	DBV Ratio	Mu-Meter	Verbal
1	1.80 and below	0.50 and above	Good
2	1.90 to 2.50	0.49 to 0.35	Medium
3	2.60 and above	0.34 and below	Poor

NOTE: At the lower end of the "medium" range a potential aquaplaning condition may exist with some aircraft under wet conditions.

SOURCE: Letter to AFWL from Procurement Executive, Ministry of Defense, London, dated 26 July 1973.

APPENDIX B

VERIFICATION OF THE NASA DBV/SDR RELATIONSHIP USING DATA FROM THE F-4 RAIN TIRE PROGRAM

The report of the skid resistance tests conducted at the Air Force Flight Test Center in support of the F-4 rain tire program is contained in AFWL-TR-74-90 (ref 21). Included in the appendices to this referenced report are the skid resistance data gathered during the tests.

Soon after the completion of the F-4 rain tire tests, the Aeronautical Systems Division released a preliminary report containing detailed data on the aircraft landings (ref 22). Four landings (aircraft operations numbers 24, 26, 27 and 28) made during the tests provided data that could be used to check the validity of the NASA DBV/SDR relationship shown in figure 8. These data (extracted from references 21 and 22) are summarized in table 12.

The method used to verify the NASA DBV/SDR relationship required use of the F-4CD Minimum Landing Roll Distance chart which is reproduced from TO 1F-4C-1 and shown in figure 43. In order to verify the accuracy of the NASA DBV/SDR relationship, it was necessary to use this figure to compute the RCR value that the aircraft "saw" in each case. This RCR value was then converted to an equivalent SDR value by the relationship shown in figure 8, and this SDR value compared to the SDR measured by the AFWL diagonally braked vehicle.

Before figure 43 could be entered to obtain the SDR "seen" by the aircraft, it was necessary to adjust and convert some of the data shown in table 12. These adjustments and conversions were:

a. The wind speed and direction were converted to an equivalent tailwind or headwind in knots.

b. The pressure altitude in inches of mercury was converted to the equivalent pressure altitude in feet.

c. The SDR values in test section B were linearly interpolated for the value corresponding to 7 minutes after wetting (when the aircraft actually passed through this test section). Likewise, the SDR values in test section D were linearly interpolated for the value corresponding to 3 minutes after wetting (when the aircraft actually passed through this test section). These two

Table 12

SUMMARY OF SPECIFIC DATA FROM SELECTED AIRCRAFT OPERATIONS DURING THE F-4 RAIN TIRE TESTS

Operation No.	Aircraft Gross Weight Pounds	Wind Speed Knots	Wind Direction Degrees	Temperature C	Pressure Altitude Inches Hg	Final Ground Speed Knots	Ground Distance Feet	Final Longitudinal Deceleration Ft/Sec²	Test Section B Time After Wetting for DBV, Minutes	Test Section B SDR	Test Section D Time After Wetting for DBV, Minutes	Test Section D SDR
24	40,126	6.4	235	12.0	27.520	70.24	10,624.95	2.87	0.68	1.82	0.50	2.00
									7.75	2.11	3.97	2.19
26	41,976	1.6	240	4.0	27.699	31.68	10,575.55	10.95				
									No Data	No Data	1.13	2.00
									10.57	2.64	6.87	2.36
27	37,651	3.0	217	7.0	27.707	25.28	10,496.16	5.76				
									0.65	2.04	0.39	2.24
									7.62	2.25	4.48	2.22
28	34,176	1.8	220	9.0	27.710	28.03	9,239.55	11.48				
									0.40	[illegible]	0.10	2.06
									8.35	2.29	4.55	2.45

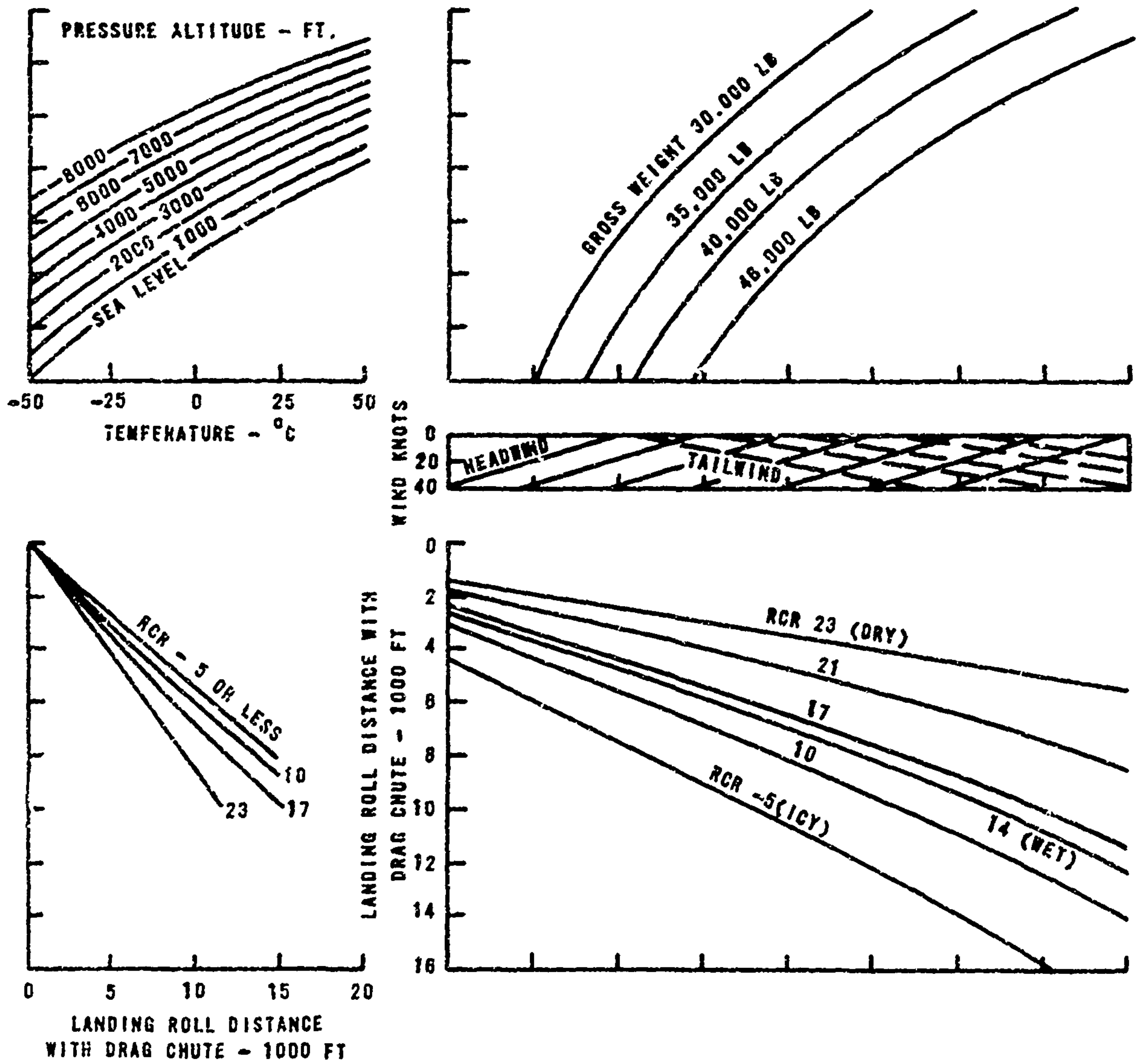


Figure 43. Minimum Landing Roll Distance

interpolated values were then averaged to give the overall SDR value for the runway. The one exception to this procedure was Operation No. 27, for which data from Test Section D only was used; this was necessitated by the lack of complete data for Test Section B.

d. The ground distance was adjusted to add on the additional distance that would have been required to bring the aircraft to a complete stop. This was done by assuming the final longitudinal deceleration would be constantly maintained until the aircraft stopped. The additional time required to stop the aircraft was determined from the relationship:

$$t = \frac{V_i}{d}$$

where t = time to stop the aircraft in seconds

V_i = final ground speed from Table 12 converted to feet per second.

d = final longitudinal deceleration from Table 12.

The additional stopping distance was determined from the relationship:

$$a = V_i t - 1/2\ dt^2$$

where a = additional stopping distance in feet

t = time (from above)

V_i = final ground speed from Table 12 converted to feet per second.

d = final longitudinal deceleration from Table 12.

The adjusted and converted data used to obtain the RCR "seen" by the aircraft in each case are shown in table 13.

As can be observed, the SDR values equivalent to the RCR "seen" by the aircraft are in fairly close agreement with the overall SDR values. Perhaps more encouraging is the fact that the overall SDR values as determined by the

Table 13

ADJUSTED VALUES USED TO FIND RCR "SEEN" BY AIRCRAFT

Operation No.	Wind Speed in Knots*	Pressure Altitude Feet	Overall SDR Value	Adjusted Ground Distance Feet	RCR "Seen" by Aircraft (Fig 43)	Equivalent SDR (Fig 8)
24	6.3H	2300	2.11	13073.40	10	2.10
26	1.5H	2100	2.12	10967.03	13	1.80
27	2.9H	2100	2.23	10970.38	13	1.80
28	1.7H	2100	2.28	9531.95	12	1.90

* T = Tailwind
  H = Headwind

diagonally braked vehicle are conservative in each case. In other words, the diagonally braked vehicle never predicted that it would take less distance to stop the aircraft than it actually took.

Admittedly it would take many more data points to prove conclusively that the NASA DBV/SDR relationship is valid for the F-4 aircraft. Until such time as such additional data become available, AFWL supports interim use of the NASA DBV/SDR relationship to determine equivalent RCR values for runways tested.

APPENDIX C

TECHNICAL SPECIFICATIONS FOR CONSTRUCTION OF POROUS FRICTION PAVEMENT OVERLAY AT PEASE AFB, NH

POROUS FRICTION COURSE (PFC) (CENTRAL PLANT HOT MIX)

8-01. DESCRIPTION: This item shall consist of a plant mixed, hot laid, porous friction course, composed of a single application of bituminous material and aggregate 5/8" to 7/8" thick placed in accordance with these specifications and conforming to the dimensions and typical cross sections as shown on the plans, and/or as directed by the Contracting Officer.

8-02. MATERIAL:

a. The aggregates shall be crushed stone from deposits of granite, or basalt as approved by the Contracting Officer. Limestone or dolomite will not be used. The crushed stone shall consist of clean, sound, durable fragments free from an excess of flat, elongated, soft or disintegrated pieces, dust, dirt, or other objectionable matter. The aggregate shall contain no more than eight percent by weight of flat or elongated pieces. The course aggregate retained on the No. 4 sieve shall have a percent of wear not more than 25 after 500 revolutions as determined by ASTM C-131. It shall show no signs of disintegration nor shall the sodium sulfate soundness loss exceed 9 percent, or the magnesium soundness loss exceed 12 percent, when tested in accordance with ASTM C-88. Crushing of the aggregate shall result in a product in which the coarse aggregate (retained on No. 4 sieve) shall have at least 75 percent by weight of particles with two or more fractured faces and 100 percent by weight of particles with one or more fractured faces. The aggregate shall be of such a nature that when thoroughly coated with asphalt, the retained bituminous film shall be at least 95 percent and show no evidence of stripping when tested in accordance with ASTM D-1644. The above tests shall be performed by an approved testing lab at the contractor's expense, and certificates of conformance shall be submitted to the Contracting Officer for approval prior to the use of any material. A one-cubic foot sample of the proposed aggregate shall be submitted for approval to the Contracting Officer.

b. Filler. Hydrated lime, in the amount of 1.5 percent, is to be used to

furnish a part of the specified percentage of material passing the 200 sieve. If additional material of this grading is required, it shall consist of crusher dust of siliceous or igneous material approved by the Contracting Officer or crushed limestone of the following gradation:

Sieve	Percent Passing by Weight
50	100
200	75-100

c. Bituminous Material: The asphalt cement shall be of 120-150 penetration grade in accordance with ASTM D5-65, or AC-5 viscosity grade according to ASTM D-88-68. Certificates of conformance shall be submitted to the Contracting Officer.

8-03. COMPOSITION:

a. Composition of Mixtures. The bituminous plant mix shall be composed of a mixture of aggregate, filler if required, and bituminous material. The several aggregate fractions shall be sized, uniformed, graded, and combined in such proportions that the resulting mixture meets the grading requirements of the job mix formula.

b. Mix Production. The asphalt binder shall be heated to a temperature of 240 ± 35 degrees F. The aggregates are to be heated to a temperature of 212 ± 36 degrees F. At the time of mixing the temperature of the aggregates and binder shall be prohibited and reheating of condemned mixtures because of overheating shall likewise be prohibited. The heated aggregates and asphalt are to be thoroughly mixed and the aggregate fully coated.

c. Job Mix Formula. Work shall not begin nor shall any mixture be accepted until the contractor has submitted samples of the materials intended for use, along with a satisfactory job mix formula. The job-mix shall be in effect until modified in writing by the Contracting Officer. The job-mix shall establish a single percentage of aggregate passing each required sieve size, a single percentage of bituminous material to be added to the aggregate and a single temperature at which the mixture is to be delivered at the point of discharge. The gradation in table 1 represents the limits which shall determine suitability of aggregate for use from the sources of supply. The final gradation decided on within the limits designated in the table shall be graded from coarse to fine and shall not vary from the low limit on one sieve to the high limit on the

adjacent sieves, or vice versa. The bituminous content of the mixture shall be calculated on the percentage basis by weight of the total mix.

8-04. TEST SECTION: Trial batches of the porous friction course mixture shall be made up in the plant the contractor proposes to use with the aggregate proportioned in the various hot bins to produce the required aggregate grading. These batches shall be laid as preliminary trials on areas as designated by the Contracting Officer using the spreading and compaction equipment the contractor proposes to use. Should the above preliminary trials indicate that the mixture with the binder at the specified proportion or the construction and mixing procedures are unsatisfactory, the properties of binder or construction and mixing procedures shall be changed, and further trial sections shall be constructed with modified mixtures or construction procedures until it is demonstrated that a satisfactory mixture has been achieved. The contractor shall not begin the general placement of the porous friction course until (1) a satisfactory mixture has been constructed in the test section, and (2) the mix design and the construction and mixing procedures have been approved in writing by the Contracting Officer. A sample of the coarse and fine aggregates shall be washed to determine the percentage of the total material passing the No. 200 mesh sieve. Of the amount of material passing the No. 200 mesh sieve, at lease one half shall pass the No. 200 mesh sieve by dry sieving. After the job-mix formula is established, all mixtures furnished for the project shall conform thereto within the following tolerances:

Aggregate passing #4 sieve or larger	± 4%
Aggregate passing #8 sieve	± 3%
Aggregate passing #200 sieve	± 1.5%
Bituminous	± 0.25%
Temperature of mix	± 15 degrees F.
Temperature of placement	± 25 degrees F.

Should a change in sources of materials be made, a new job-mix formula shall be established and approved by the Contracting Officer before the new material is used on the project. When unsatisfactory results or other conditions make it necessary, the Contracting Officer may establish a new job mix formula. The combined mineral aggregate for the porous friction source shall be of such size that the percentage composition by weight as determined by laboratory sieve, will conform to the gradation of table 1, when tested in accordance with ASTM C-117 and ASTM C-136. The percent by weight for the bituminous material shall be within the limits specified.

Table 1

AGGREGATE-BITUMINOUS SURFACE COURSE

Sieve Designation (Square Openings)	Percentage by Weight Passing Sieves
1/2"	100
3/8"	90-100
#4	30-40
#8	17-23
#200	3-5

Bitumin, percent --5.0-6.0%

8-05. BATCH PLANT:

a. Mixing Plant. The mixing plant shall be designed, coordinated, and operated so as to produce a mixture within the job-mix formula. The plant shall be a weight-batch type and shall have a minimum capacity of 50 tons per hour. Any plant used for the preparation of bituminous mixtures shall conform to all the requirements specified.

b. Plant Scales. Plant scales for any weight box or hopper shall be of standard make and design, either of the beam or springless dial type, sensitive to 1/2 of one percent of the maximum load that may be required. When of the beam type, there shall be a separate beam for each size aggregate, with a single telltale actuated for each separate beam and a tare beam for balancing the hopper. Standard test weights shall be provided for checking the accuracy of the plant scales.

c. Equipment for Preparation of Bituminous Material. Tanks for storage of bituminous material shall be capable of heating the material under effective and positive control, at all times, to the temperature requirements specified herein. Heating shall be accomplished by steam coils, electricity, or other means that will allow no direct flame to come in contact with the heating tank. The circulating system for the bituminous material shall be of adequate size to insure proper and continuous circulation between storage tank and mixer during the entire operating period. Pipe lines and fittings shall be steam-jacketed or otherwise properly insulated to prevent heat loss. The storage tank capacity shall be sufficient for at least a one-day run.

d. Feeder for Dryer. The plant shall be equipped with an accurate machanical means for uniformly feeding each mineral aggregate into the dryer. The aggregates shall be proportioned by means of fold bins or by a reclaiming tunnel under the separate stockpiles. When bins are used, the cold aggregates shall be proportioned by at least three bins or compartments of sufficient capacity to store the amount of aggregate required for continuous operation. Each bin shall be controlled by a mechanical device which will provide a continuous and uniform flow of materials to the dryer. Each cold aggregate shall be proportioned in a separate bin or compartment. When a reclaiming tunnel is used, a mechanical device shall be provided at each stockpile opening. The mechanical devices shall be controlled to provide a uniform and continuous flow of materials in the desired proportions to the dryer. At the start of the work, the contractor shall furnish the Contracting Officer with a calibration chart for each cold feed gate, accurately indicating the rate of flow of each aggregate for the entire range of gate openings. The chart shall be arranged to show the rate of flow in pounds or tons per hour, per inch of gate openings.

e. Dryers. A rotary dryer capable of thoroughly drying and heating the mineral aggregates to the temperature requirements set forth in the specification shall be provided. When porous aggregates (basalt, and similar materials) that readily absorb water are used or when one dryer does not thoroughly dry the aggregates due to climatic conditions, sufficient additional dryers shall be provided to thoroughly dry and properly heat the aggregates as directed by the Contracting Officer.

f. Screens. Plant screens capable of screening all aggregates to the specified sizes and proportions and having normal capacities in excess of the full capacity of the mixer shall be provided.

g. Bins. The plant shall include storage bins of sufficient capacity to supply the mixer when it is operating at full capacity. The bins shall be divided into at least three compartments arranged to insure separate and adequate storage of appropriate fractions of the aggregate. Each compartment shall be provided with an overflow pipe of such size and at such location as to prevent any backing up of the material into other bins. Adequate dry storage shall be provided for mineral filler, and provision shall be made for accurately weighing or proportioning the mineral filler into the mixtures.

h. Bituminous Control Unit. Satisfactory means shall be provided to obtain the proper amount of bituminous material in the mix within the tolerances

specified by the job-mix formula, either by weighing, metering, or volumetric measurements. Suitable means shall be provided, either by steam-jacketing or other methods of insulation, for maintaining the specified temperature of the bituminous material in the pipe lines, meters, weight buckets, spray bars, and other containers of flow lines.

i. Thermometric Equipment. An armored thermometer with a range from 150 degrees to 350 degrees F. shall be fixed in the bituminous feed line at a suitable location near the discharge valve at a mixer unit. The plant shall be further equipped with an approved dial-scale mercury-actuated thermometer, an electric pyrometer, or other approved thermometric instruments, so placed at the discharge chute of the dryer as to automatically register or indicate the temperature of the heated aggregate.

j. Control of Mixing Time. The plant shall be equipped with positive means to govern the time of mixing and to maintain it constant, unless otherwise directed by the Contracting Officer. The time of mixing shall be considered as the total or dry- and wet-mixing time for batch plants.

k. Dust Collectors. When plants are located in any vicinity where dust may be objectionable, the plant shall be equipped with dust collectors. Provisions shall be made to waste the material so collected or to return a controlled portion of it uniformly to the mixture, as the Contracting Officer may direct.

8-06. CONSTRUCTION METHODS:

a. Weather and Seasonal Limitations. The porous friction course shall be constructed only when the subgrade, base course, or existing pavement is dry, and not frozen, and when the weather is not rainy or foggy. The pavement surface shall be clean and dry at all times during construction. Asphalt courses shall be constructed only when the temperature is at least 50 degrees F. and rising, unless otherwise directed by the Contracting Officer.

b. Transportation and Delivery of Mixture. The mixture shall be placed at a temperature of not less than 167 degrees F. or as directed by the Contracting Officer, to yield a nominal compacted thickness of 3/4 of an inch. Loads shall be sent from the plant so that all spreading and compacting of the mixture may be accomplished during the daylight hours. Excessive waiting or delay of haul trucks at the job site shall not be allowed; mix supplied at temperatures below the minimum as stated above shall be unacceptable. Bleeding and rich spots as a result of segregation during transportation will not be accepted.

c. Spreading and Laying. The minimum atmosphere temperature shall be as stated in paragraph a. above and the temperature requirement as stated in paragraph b. above and as follows:

The plant mixed porous friction course mixture shall be dumped from the haul units directly into the laydown machine hopper. Dumping plant-mixed porous friction course mixture onto the pavement ahead of the laydown machine will not be permitted. Two laydown machines, and three tandem steel rollers, and one pneumatic-tired roller, all in good working condition, shall be on the job site prior to commencing the laydown operation. Spreading of the mixture shall be done carefully with particular attention given to making the operation as continuous as possible.

d. Compaction of Mixture. The porous friction course shall be placed on a compacted finegrained level course or the prepared existing surface as applicable with a conventional laying machine. The surface shall receive a tack coat prior to construction of the porous friction course. Following placement, the porous friction course is to be compacted at a temperature not less than 158 degrees F. with a steel wheel roller weighing six to ten tons. No more than four complete passes of the steel wheel roller shall be made unless directed otherwise by the Contracting Officer. Care should be taken to avoid (a) overrolling or (b) rolling when material is too cool. To prevent adhesion of the mixture to the roller, the wheels shall be kept properly moistened, but without excessive-water. The porous friction course shall be rolled in a longitudinal direction. Rolling operations shall be conducted in such a manner that shoving, distortion, or stripping will not develop beneath the roller. Rolling the porous friction course with a 6-10 ton self-propelled pneumatic-tired roller may be required as directed by the Contracting Officer; however, such rolling shall not proceed earlier than 2 hours nor later than 24 hours after the porous friction course has been placed. The compacted thickness of the porous friction course will be 3/4 inches thick and shall comply with the lines and grades as specified on the plans. Any mixture which becomes loose and broken, mixed with dirt, or in any way defective, shall be removed and replaced, at the contractor's expense, with fresh mixture and immediately compacted to conform to the surrounding area.

e. Joints. All joints shall conform to:

(1) General. All joints shall present the same uniformity of texture, density, smoothness as other sections of the course. The joints between old and

new pavements or between successive days work shall be carefully made in such manner as to insure a continuous bond between old and new sections of the course.

(2) Longitudinal. Longitudinal joints in the surface course shall be placed so that the joint will not coincide with that of the leveling course and will break by at least one foot.

8-07. SAMPLING PAVEMENTS AND MIXTURES. Suitably sized samples, as required by the Contracting Officer, for the determination of thickness and density of the constructed pavements, shall be removed by the contractor at his expense. The contractor shall furnish all tools and labor for taking samples and replacing the pavements, at his expense, to the satisfaction of the Contracting Officer. All tests necessary to determine conformance with the requirements specified herein will be performed by an approved testing laboratory at the contractor's expense. Samples of the plant mixtures will be taken and tested to determine conformance to specified pavement test properties, bitumen content, and gradation requirements. No payment will be made for the areas of pavement deficient in composition, density, or thickness until they are removed and replaced by the contractor as directed by the Contracting Officer.

8-08. PROTECTION OF PAVEMENT: After final rolling, no vehicular traffic of any kind shall be permitted on the pavement until it has cooled and hardened, and in no case less than 24 hours. The area shall be protected from aircraft traffic for seven days after construction.

8-09. INSPECTION OF PLANT AND EQUIPMENT: The Contracting Officer shall have access at all times to all parts of the paving plant for checking the adequacy of the equipment in use, inspecting the operation of the plant, verifying weights, proportions, and character of materials, and checking temperatures being maintained in the preparation of the mixtures.

8-10. TESTING AND MATERIAL REQUIREMENTS:

Test and Short Title

ASTM C-88, Soundness
ASTM C-117, Gradation
ASTM C-127, Specific Gravity
ASTM C-128, Specific Gravity
ASTM C-131, Abrasion
ASTM C-136, Gradation
ASTM D-423, Liquid Limit

<u>Test and Short Title</u> (Cont'd)

ASTM D-424, Plastic Limit and Plasticity Index
ASTM D-1664, Stripping
AASHO T-102, Swell

<u>Material and Short Title</u>

ASTM D-242, Filler
ASSHO M-20, Penetration Method Asphalt Cement
AASHO M-226, Viscosity Method Asphalt Cement

APPENDIX D

LETTER REPORT *
Reflective Cracking in Porous Friction Surface at Pease AFB, NH

INTRODUCTION

This report presents an evaluation of the reported reflective cracking in the porous friction surface (PFS) runway at Pease AFB, NH. An inspection of the PFS was conducted on 13 February 1973 by representatives of the following organizations: Hq SAC(DE), AFCEC, AFWL, Base Civil Engineer, and Base Operations.

BACKGROUND

The PFS was constructed on the central 8420 feet of the runway at Pease AFB in September 1972. With the exception of approximately 1270 feet at the north end of the runway, the PFS was constructed directly over an aged and partially cracked asphaltic concrete (AC) pavement. The only surface preparation in this area (7150 feet) prior to PFS construction consisted of filling surface cracks larger than 3/8-inch with joint sealer. The remaining 1270 feet at the north end of the runway, however, was heater-planed and overlaid with conventional AC prior to PFS construction. The AC leveling course at the north end was constructed to correct the poor surface drainage and slight rutting that existed in this area of the runway. Because of economic considerations, the recommended AC leveling course between the PFS and old AC was deleted except as noted.

RESULTS

Surface Conditions Beneath PFS

The condition of the pavement directly beneath the new PFS is believed to be the key to the reflective cracking reported at Pease AFB. The PFS subsurface on this runway can be divided into three distinct conditions as shown by the sketch in Figure 1.

Condition 1. The pavement directly beneath the PFS at the south end of the runway (condition 1) is characterized by (a) longitudinal distress cracks on 3 to 4 feet centers in a region approximately 20 feet

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to each side of the runway centerline, and (b) longitudinal construction lane cracks on approximately 10 feet centers. The surface condition in this area can be shown by the photographs taken in April 1972 (Figures 2 and 3). For the most part, the distress cracks are longitudinal with occasional random transverse cracks. In addition, a 10 foot straight edge survey, conducted perpendicular to the centerline prior to construction, revealed that there was some surface settlement associated with these distress cracks.

Condition 2. The pavement directly beneath the PFS in the central portion of the runway (Condition 2) is generally good structurally, and has good surface drainage. The crack pattern consists primarily of longitudinal lane construction cracks on approximately 10 feet centers. No distress cracking was noted in this area.

Condition 3. The crack pattern of the old pavement surface at the north end of the runway was similar to that at the south end. The surface drainage characteristics in this area, however, were poor and in some spots the drainage was toward the runway centerline. In addition, there was slight rutting in some spots in the major wheel path areas, resulting in the ponding of water. A photograph taken in this area in April 1972 is shown in Figure 4. This area, however, was heater planed and overlaid with conventional AC (0 to 9 inches thick) to correct the transverse drainage problems prior to the PFS construction. This area provides condition 3 in which the pavement characterized by similar distress cracks as in condition 1 received an AC leveling course prior to construction of the PFS.

PFS Immediately After Construction

Figure 5 is a photograph taken from the south end of the PFS (Condition 1 Area) on 27 September 1972. This photograph shows an overview of the PFS nine days after the PFS construction was completed and immediately after the aircraft (FB-111 and KC-135) began to return. Figure 6 shows the tire marks of the initial landing of a KC-135 on the new PFS in the condition 1 area. Also included is a photograph (Figure 7) which shows the difference in surface texture between the PFS and the conventional AC. This photograph was taken at the transition between the new PFS and new AC overlay at north end of the runways (Condition 3 Area).

Findings on 13 February 1972

Condition 1 Area. We found that the reported cracks in the PFS were reflective cracks rather than some characteristic of the PFS design and were confined to the condition 1 area of the runway. These surface cracks were primarily the reflection of the wide distress cracks in the

old pavement. The construction lane cracks did not appear to be reflecting except where distress settlement had developed in the lane crack area. Most of the reflective cracks were longitudinal and were located within 20 feet of the runway centerline.

The photographs shown in Figure 8 are typical of the reflective cracks observed in this area. Figure 9 in a close up of one of the largest cracks (approximately 1-inch wide at top). In a few places, transverse reflective cracks occurred in conjunction with the longitudinal cracks; an example is shown in Figure 10. Note the close comparison between the crack patterns in the above photographs to that of the underlying pavement surface shown in Figures 2 and 3.

Condition 2 Area. The PFS in the central portion of the runway showed no evidence of reflective cracking and appeared to be in excellent condition. A photograph at the center of the runway (facing north) is shown in Figure 11. It should be noted that (a) the PFS in this area was constructed directly over the existing old AC pavement, (b) the longitudinal lane cracks in the old pavement have not reflected through at this time, and (c) there is apparently good bond between the old AC and the new 3/4-inch PFS. This area should continue to be observed as the construction lane cracks may eventually reflect through.

Condition 3 Area. The PFS at the north end of the runway, like that in the central portion, showed no evidence of cracking and appeared to be in excellent condition. It should be noted that the distress condition of the old pavement in this area was similar to that in the condition 1 area, however, the condition 3 area received an AC overlay prior to the construction of the PFS. This demonstrates the value of an AC overlay over an aged pavement surface characterized with distress cracking.

Flexibility of PFS. The resistance of PFS to reflective cracking can be demonstrated by the photograph in Figure 12. This photograph was taken at the transition point between the PFS and the conventional AC at the south end. Note that the crack in the AC, which underlays the PFS, has not reflected through the PFS. This suggests that it takes a significant movement beneath the PFS before a reflective crack is visible. The PFS design is significantly more flexible than a conventional AC and is normally more resistant to this type cracking.

CONCLUSIONS

1. The reported cracks in the PFS at Pease AFB are reflective cracks from the existing distress cracks in the old pavement structure, rather than some characteristic of the PFS design. These cracks are

confined to the south touchdown area of the runway and are located generally within 20 feet of the runway centerline.

2. The reflective cracks have occurred only in the area where the 3/4-inch PFS was constructed directly over an old existing AC pavement surface containing numerous distress cracks (See Figures 2 and 3). In the area where a similar cracked surface was overlaid with a conventional AC prior to constructing the PFS, no reflective cracking has developed. In addition, the area where the PFS was constructed directly over an old pavement containing only construction lane cracks, no reflective cracking has yet occurred.

3. The cracks are primarily longitudinal in nature, although occasionally, transverse cracks have reflected through.

4. Although these reflective cracks are undesirable, we feel that they pose no immediate problem to aircraft operations.

5. The reflective cracking noted could have been avoided or better controlled had the old existing pavement received an AC overlay prior to constructing the PFS.

6. The pavement structure beneath a PFS must be structurally sound and free of major surface cracks. The experience at Pease AFB supports prior contentions that, under most conditions, an AC leveling course is required between an aged AC pavement surface and a PFS. This is to ensure that a proper drainage platform is provided beneath the PFS, that the old pavement surface is sealed, and that a transition zone is provided between the pavement materials for control of temperature and load related movements. The experience at Pease AFB also suggests, however, that PFS can perform satisfactorily when constructed directly over an aged AC containing minor construction cracks, provided there is no load distress associated with these cracks.

RECOMMENDATIONS

1. Although the reflective cracks appear to pose no immediate operational problems, the Base Civil Engineer should be prepared to take the following corrective measures in the event the area around these cracks begin to ravel:

a) The cracks in the old pavement (below PFS) should be filled, and the walls of the PFS cracks should be coated with a soft asphalt (i.e., AC-5 at 240°F), or a fast curing RC asphalt, or "Petroset" by Phillips Petroleum. This action should be sufficient for the smaller width cracks.

b) The large cracks (3/4-inch or wider at top) should be treated as in "a" above, then filled with an asphalt mixture following the PFS design; then the fill material should be compacted in the crack with a steel wheel roller. If possible the PFS mixture should be obtained from a hot mix plant. If this is impractical, a satisfactory mix could be prepared in the CE shops using the following formula:

1) A one size aggregate (1/4" to 3/8")
2) AC-5 asphalt binder (6 to 7 percent by weight)
3) Mixed at a temperature between 140° and 210°F.

Note also that we are speaking of a relatively small amount of material (less than 2 cu. yds.).

2. Regardless of whether the cracks begin to ravel, we suggest that the corrective actions noted in 1a and 1b above be accomplished when weather and runway down time permits as part of your routine maintenance. It would be best to accomplish this in late spring before the cracks begin to close.

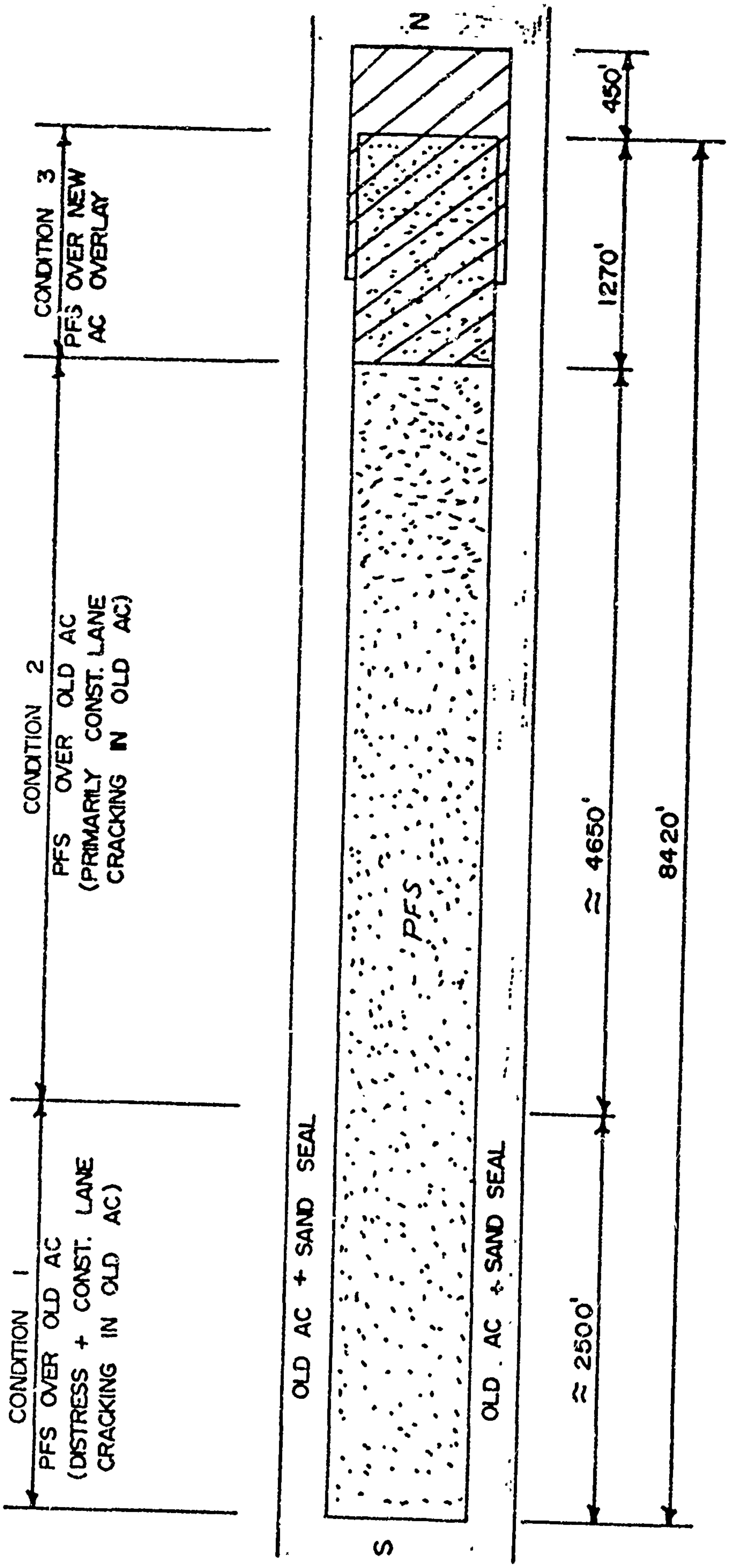

Figure 1. Layout of PFS Construction, Pease AFB, NH

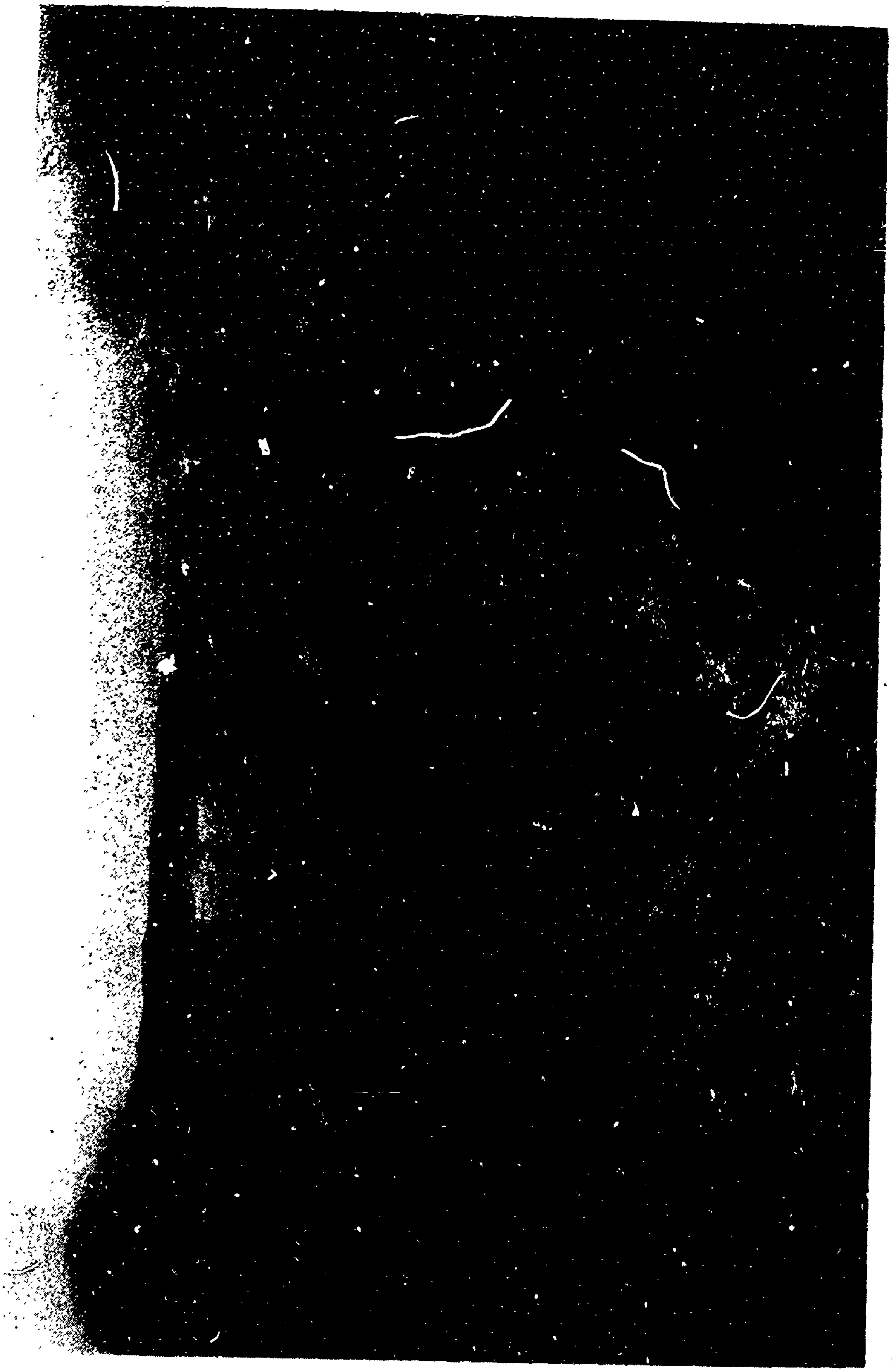

Figure 2. Old Pavement Surface Directly Under PFS, South Touchdown Area Facing North (Condition 1, Apr 72).

Figure 3. Old Pavement Surface Directly Under PFS, South Touchdown Area Facing North (Condition 1, Apr 72)

Figure 4. Old Pavement Surface, North Touchdown Area Facing South (Apr 72).

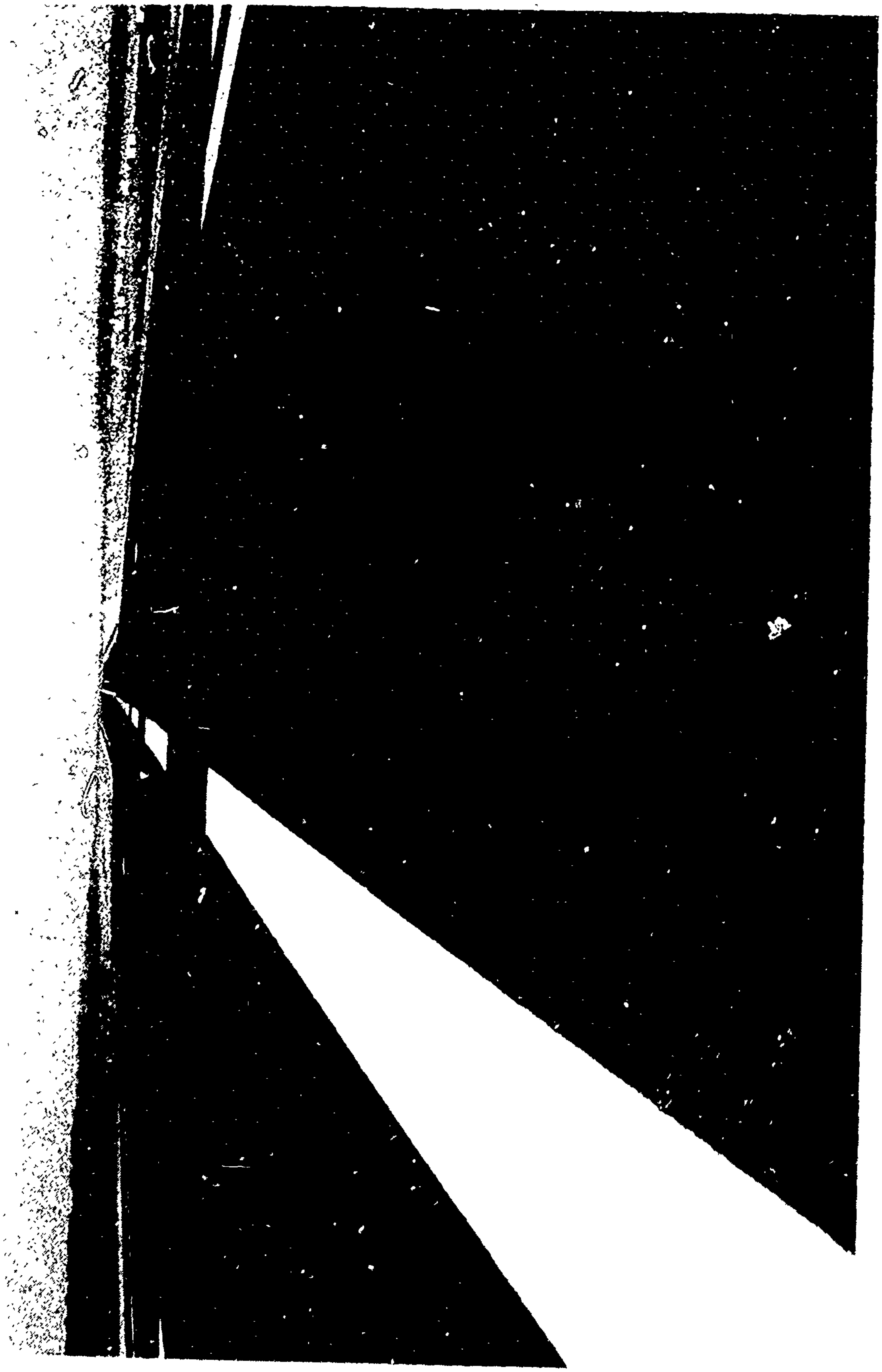

Figure 5. PFS Nine Days after Construction, South Touchdown Area (Sept 1972).

Figure 6. Tire Marks After First KC-135 Landing on New PFS (Sept 72).

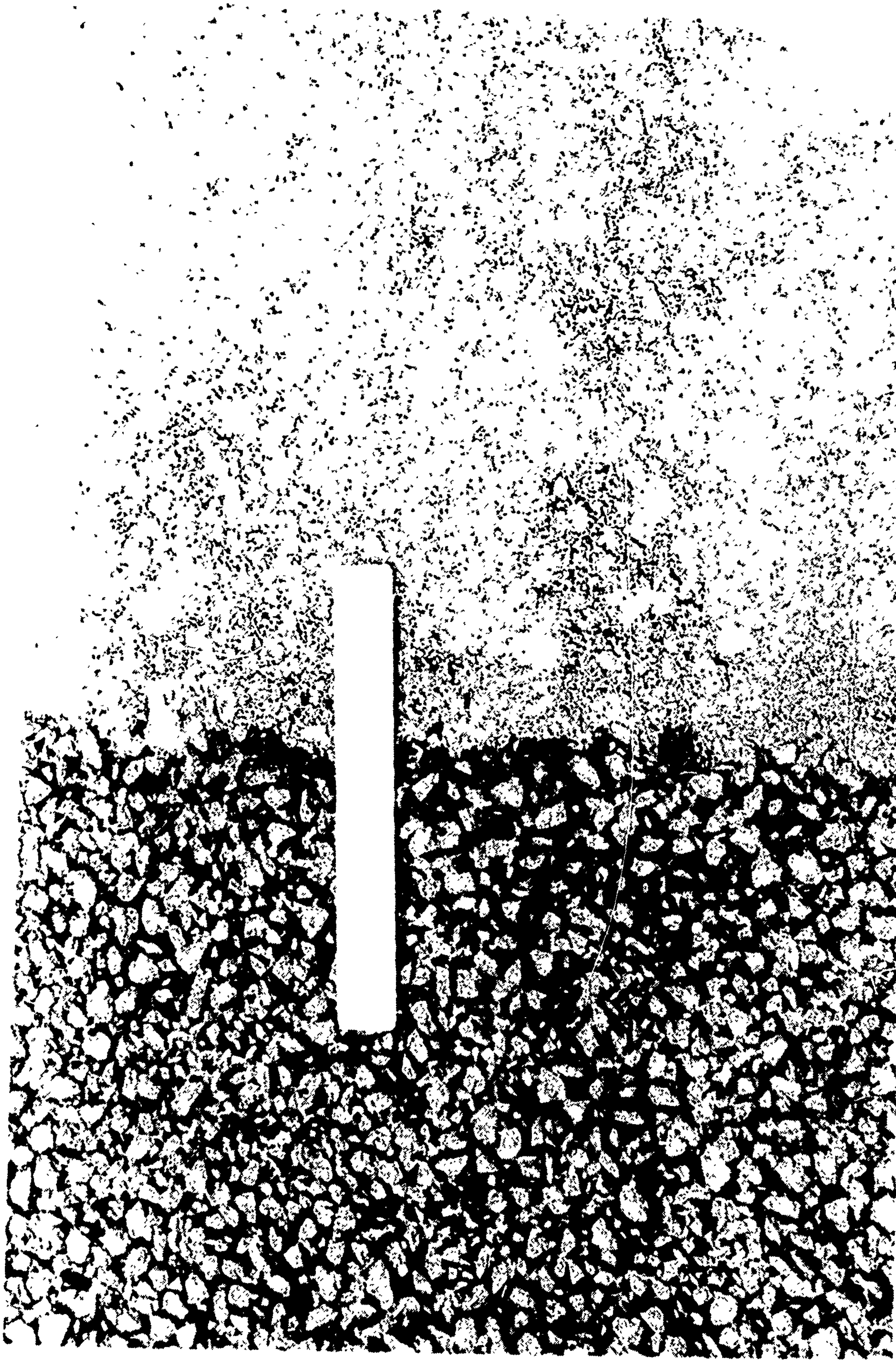

Figure 7. Surface Texture Difference Between New PFS and New AC, North Touchdown Area (Sept 72).

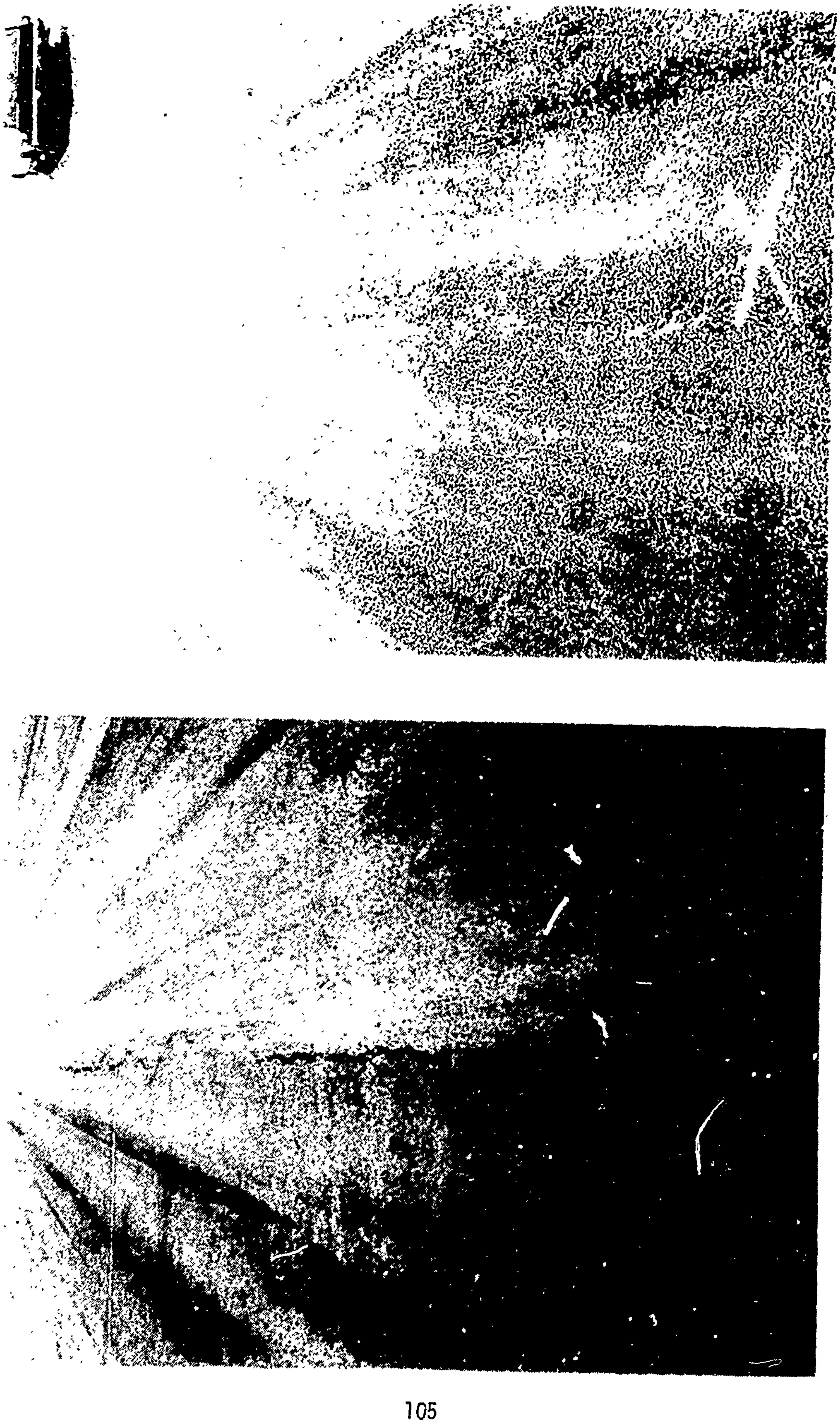

Figure 8. Typical Reflective Cracks in PFS, South Touchdown Area (Feb 73).

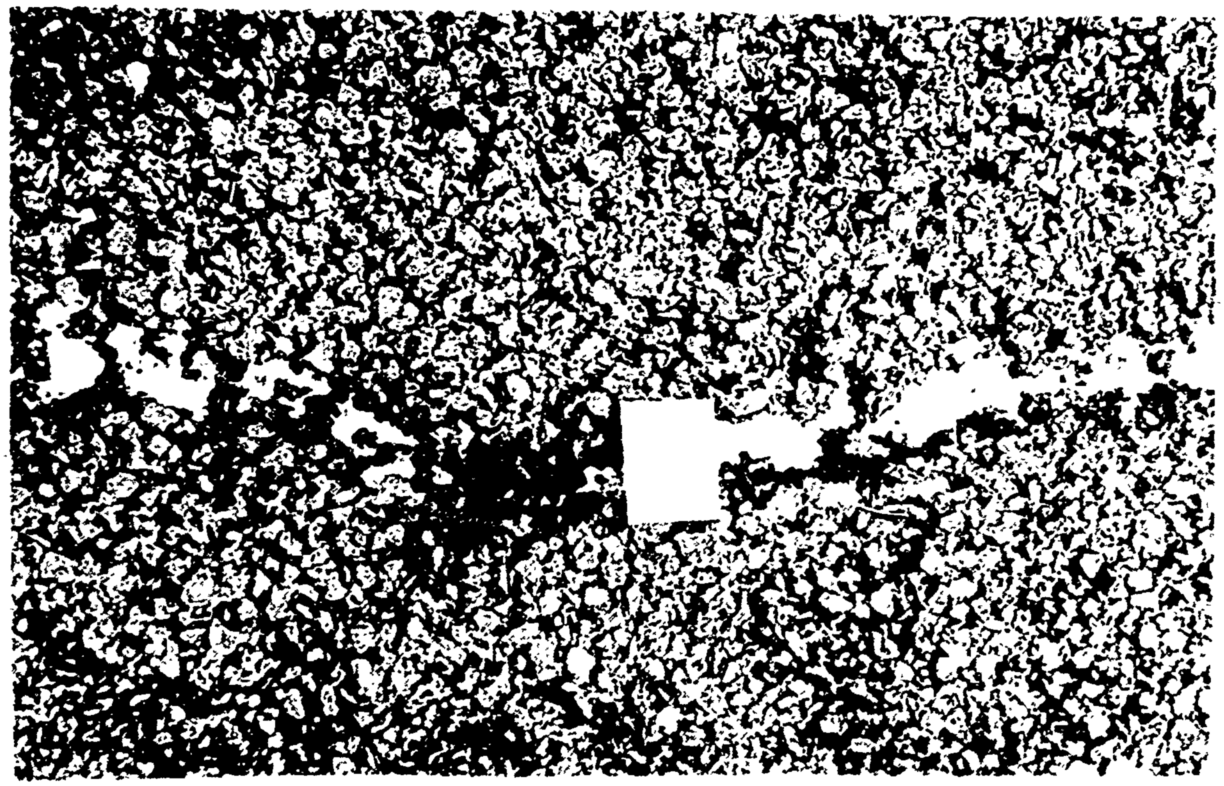

Figure 9. Close-Up View of One of the Largest Cracks in PFS, South Touchdown Area (Feb 73).

Figure 10. Example of a Transverse Reflective Crack in PFS, South Touchdown Area (Feb 73).

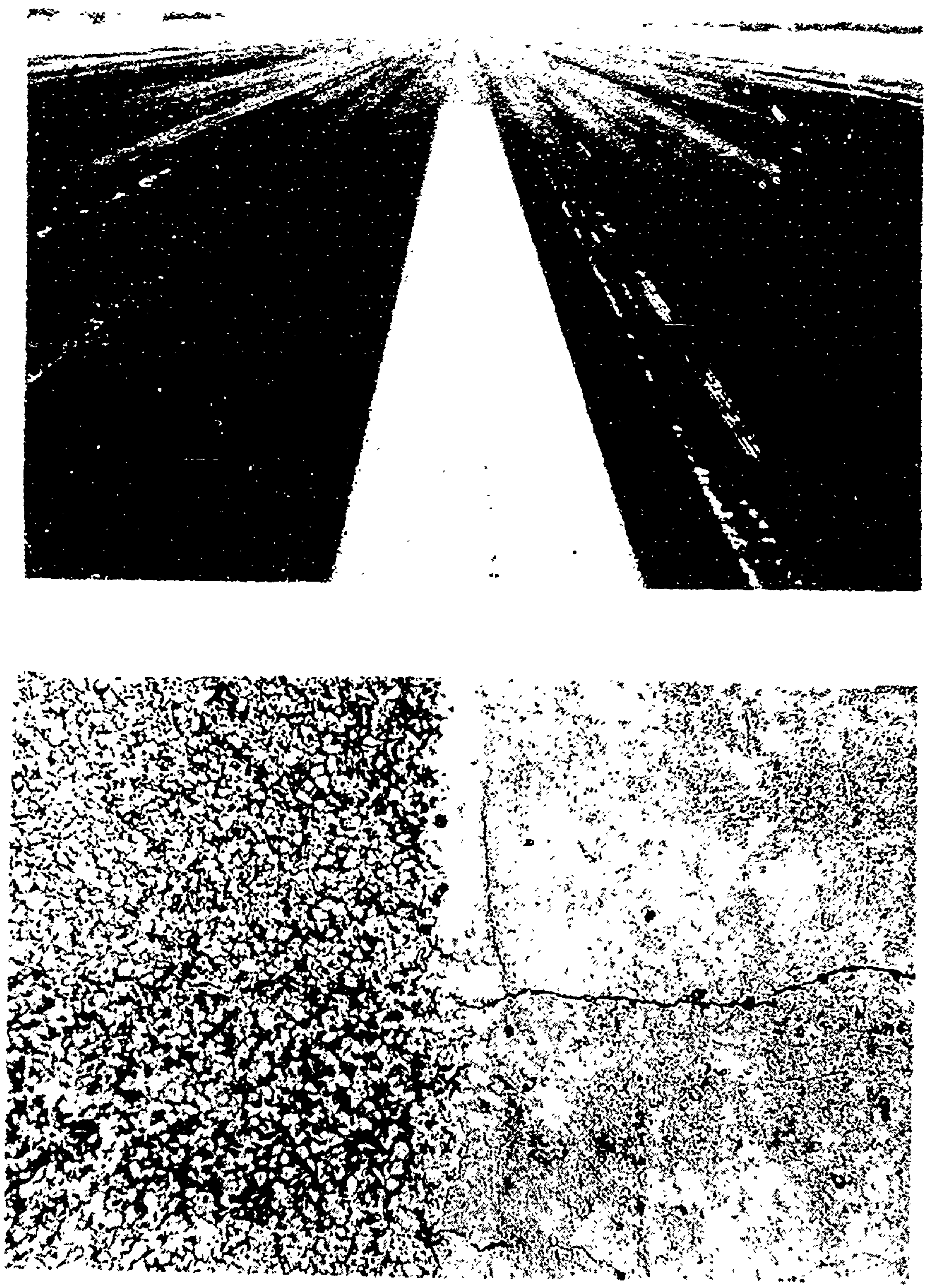

Figure 12. Example of PFS Resistance to Reflective Cracking (South End of PFS, Feb 73).

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